Final Report

REPLICA OPTICS

Prepared for
Commanding Officer
Frankford Arsenal
Philadelphia, Pennsylvania 19137

Contract DA-04-495-AMC-376(A)

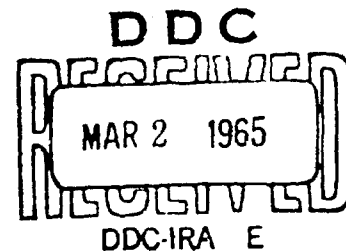EOS Report 4821-Final   26 February 1965

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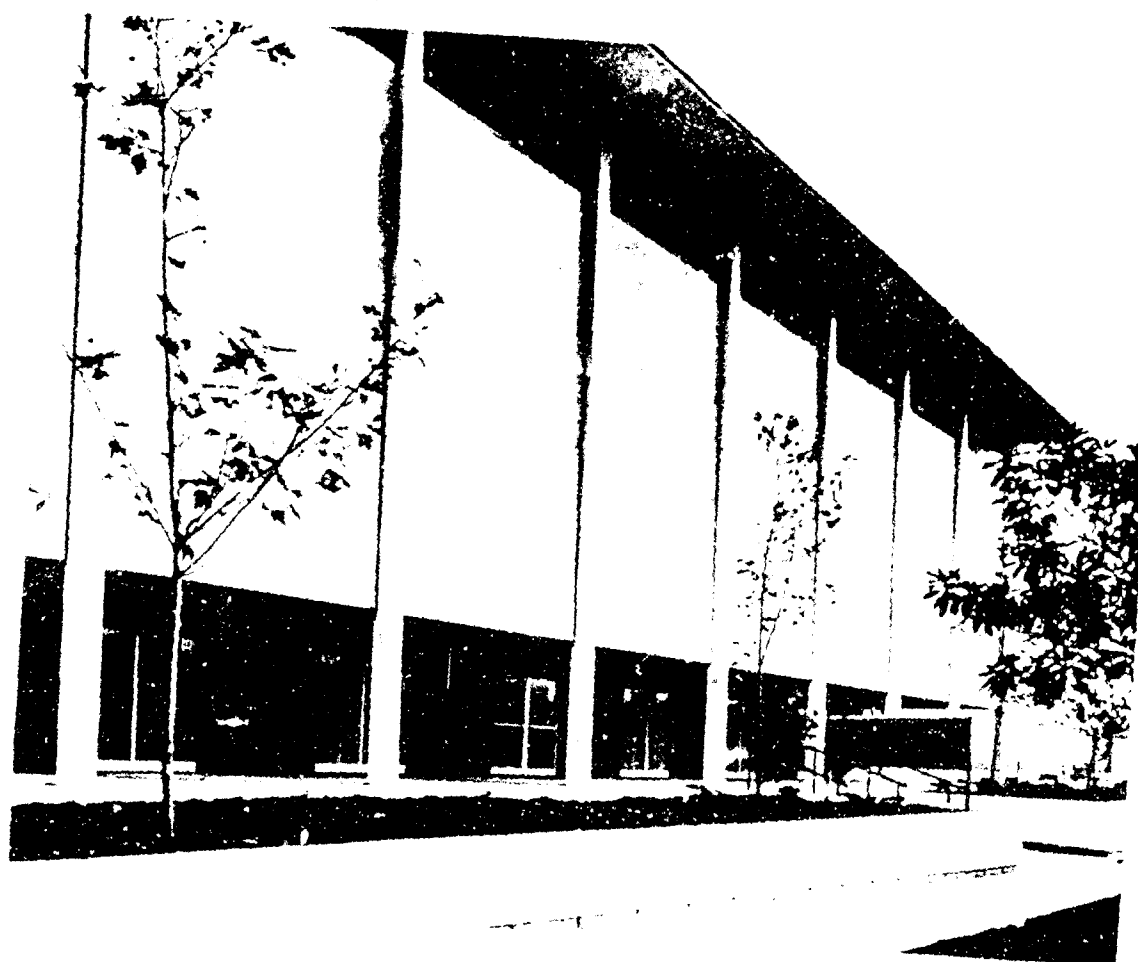Contract DA-04-495-AMC-376(A)

EOS Report 4821-Final   26 February 1965

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ABSTRACT

This report covers the period of 14 February through 12 September 1964, and is submitted in accordance with the terms of the subject contract. The scope of the program was redirected from the replication of a prototype production lot of corner prisms to the replication of concave spherical mirrors having a diameter of 4 inches. The revised objectives of this 6-month program were to procure necessary masters, fabricate, and test approximately 24 replica spheres, continue adhesives and coatings investigation, investigate advanced preform and master techniqu s, and analyze and specify production processes.

These objectives were achieved. An analysis of the replication process was updated, production processes specified, 4 masters received or fabricated, 7 submasters made, preforms procured, adhesives and coatings investigated, fixtures improved, 39 replicas plus 3 replicas by submastering made and analyzed, and the environmental and optical tests described.

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1. INTRODUCTION

Inexpensive replication of optical elements has intrigued technologists for many years. Over the past two decades, several techniques for replication of reflective optical elements have been tried and reported in the literature (Refs. 1-1 through 1-9). The feasibility of using replicating techniques for production of low-quality elements has been proven. Several companies are now producing replica optical elements for use as searchlight reflectors, low-quality imaging devices, and energy gathering devices. However, prior to Contracts DA-04-495-ORD-3332 and DA-04-495-AMC-51(A) which were conducted by Electro-Optical Systems, and were the predecessors to this program, no production type highly accurate, high-quality replica optical elements had been reported.

One promising technique for replication of accurate optics had been based on the use of thick epoxy resin castings. However, because of the imperfect dimensional stability of even the best plastics, replication techniques involving thick castings have failed to produce high-accuracy elements. The previous and present programs have circumvented the instability problem of plastics by reducing the thickness of the plastic layer as much as possible and by obtaining rigidity by using a stable preformed backing structure.

The hollow corner prism was originally chosen to demonstrate the feasibility of replicating high-quality optical elements (see Fig. 1-1). This particular component is a retrodirective reflector. Its special property is that any ray of light striking the reflector, within a wide angle of incidence, is reflected from each of its three adjacent and mutually perpendicular reflective faces and returned in the direction from which it came. Corner prisms have been widely used for such purposes as marking, sighting, ranging, and interferometry.
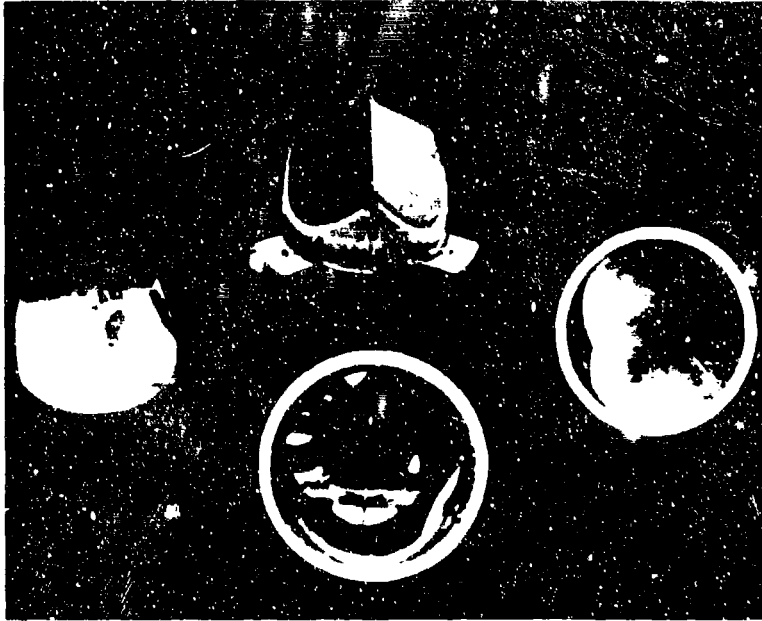
FIG. 1-1 CORNER PRISM MASTER, MASTER ASSEMBLY,
PREFORM AND REPLICA

In practice, these retrodirective reflectors usually are made in
the form of tetrahedral glass prisms. Three of the four faces are
mutually perpendicular and function as mirrors by virtue of total in-
ternal reflection. The fourth face is a window through which the light
rays enter and leave the prism. These prisms are made by grinding and
polishing and are quite expensive because of the precise tolerances
necessary for proper functioning. The replication of the prism provides
a good example for demonstrating replicating techniques. A replica
prism is the inverse of the glass prism and consists, therefore, of
three mutually perpendicular front surface flat mirrors.

At the halfway point in this program, the program scope was re-
directed to permit the fabrication of 4-inch diameter concave spherical
replica mirrors rather than retrodirective corner prisms. This re-
direction was initiated to produce deliverable hardware to be used in
environmental shock analysis. Also, a replica sphere was a closer
approximation to the current fire-control optical needs than the hollow
corner prism. Otherwise, the basic program goals remained the same.

Replication has many possible advantages over conventional grinding
and polishing techniques. These advantages include:

1. Feasibility of fabricating difficult shapes easily
2. Lower production costs
3. Improved ruggedness
4. Lower weight
5. Improved thermal properties

The latter three advantages result from the possibility of using
materials in the replication process which are structurally and/or
thermally superior to glass, even though these materials may not be
suitable for grinding and polishing. These advantages and the labora-
tory developments of the previous contracts provided incentive to
develop replication techniques further.

1.1 Objectives and Accomplishments of Contract DA-04-495-ORD-3332

The objectives of the initial contract were to improve the art of optical replication and to demonstrate this improvement by the laboratory fabrication of hollow corner reflectors having an accuracy and durability comparable to glass prisms. These objectives were accomplished.

1.2 Objectives of Contract DA-04-495-AMC-51(A)

The objective of this program was to take the corner prism replication process from the laboratory to a state of pilot production readiness.

The feasibility of producing hollow replica corner prisms of the angular accuracy specified for M-1 and M-2 corner reflectors was demonstrated using low cost, mass-produced preforms. Other detailed information relative to optical replica production was also obtained.

1.3 Objectives of Contract DA-04-495-AMC-376(A)

The basic objective of this program was originally to take the replication process as applied to corner prisms, from the state of pilot production readiness to the state of full production readiness. However, the objectives were later revised to determine whether replica mirrors could withstand the high shock loads imposed on another reflective optical element now under study. The following tasks outline the scope of the revised program work.

1.3.1 Basic Program

1. Procurement of necessary masters.
2. Intensive fabrication of production prototype replica optics. A total of approximately 24 4-inch diameter spherical or aspherical units were to be produced. Units were to be fabricated from at least two preforms each from at least five of the following types of materials:

a. Aluminum

b. Steel

c. Magnesium

d. Titanium

e. Beryllium

f. Nickel

g. Invar

h. Stainless steel

i. Reinforced plastic

3. Continuation of adhesives investigation at a reduced level.

4. Continuation of coatings investigation at a reduced level.

5. Analysis and specification of production processes.

6. Optical and environmental testing of replicas.

1.3.2 Investigation of Advanced Preform Techniques

This supplementary study was to provide data on pre-fabrication techniques that offered advantages but required further opment in order to achieve a low unit cost or suitable accuracy. ies are:

1. Electroforming

2. Plasma spraying

3. Eloxed die and investment cast

of work included:

1. Design and fabrication of tooling or mandrels

2. Fabrication of preforms

3. Fabrication and testing of replicas using these preforms

1.3.3 Investigation of Advanced Master Techniques

This supplementary study involved metal masters and a masters. Items of work included:

1. Fabrication of plane replicas from plane metal masters or replica masters in order to provide basic data for masters

2. Design and fabrication of masters

3. Fabrication of replicas using these masters

inal   5

Due to the program redirection, some of the desired breadth of the supplementary studies was necessarily sacrificed.

1.4 Program Summary

The revised objectives of the program were met. The program advanced the high accuracy, plastic-casting process to the point where production fabrication can begin.

1.4.1 Production Processes

Production processes have been detailed including an updated discussion of the high accuracy thin-film, plastic-casting process.

1.4.2 Masters

One 304 stainless steel corner prism master was procured. One green glass 4-inch diameter concave 4-inch diameter glass master with an 8.4 inch radius of curvature was obtained from Frankford Arsenal. Two convex BSC-2 glass masters 5 inches in diameter and one BSC-2 glass concave matching test plate - all with a 8.4 inch radius of curvature - were fabricated in the EOS optical shop.

Seven plastic convex submasters were made from concave spherical surfaces (either glass masters or plastic replicas).

Initial spherical replicas were made with a 14.188 inch radius of curvature Kanigen® coated steel master.

1.4.3 Preforms

Die cast aluminum hollow corner prism preforms were available from the previous program.

Thirty six machined concave spherical preforms were secured of the following materials:

1. 2024 aluminum
2. AZ-31B magnesium tooling plate
3. 4340 steel
4. 416 stainless steel
5. 6 Al-4Va-titanium

1.4.4 Adhesives

Investigations were made of epoxies, resilient and lexibilized epoxies, and polyurethanes.

1.4.5 Coatings

Vacuum deposited release coatings used included luminum, copper, gold, and silver.

Aluminum and gold reflective coatings have been used n conjunction with silicon monoxide protective layers and chromium dhesion promoting coatings.

1.4.6 Fixtures

The hollow corner prism preform tooling was reworked. acuum coating fixtures were also revised to facilitate corner prism oating.

Improved fixtures for layup, alignment and curing, nd parting of spherical replicas were designed and fabricated. Also combination knife-edge, single-wire Foucalt and Ronchi tester was esigned to test and photographically document the spherical replicas.

1.4.7 Replicas

Ten replica corner prisms and 39 spherical replicas re produced. Except for minor cosmetic defects, the spherical sters were not degraded.

1.4.8 Optical and Environmental Testing

Five spherical replicas were shock tested between 8,500 and 20,400 g's. No gross distortion resulted. Minor or im- erceptible optical distortion occurred. This test indicated the dvantages of metal-backed replica optics relative to ground and olished glass.

The Ronchigrams of all spherical replicas were hotographically recorded.

Salt spray and humidity tests, during the program and since the end of the technical effort, indicate that plastic replicas can withstand standard salt spray and humidity tests.

High and low temperature cycling and limited shelf life tests revealed no optical or mechanical degradation.

1.5 Conclusions

This program has improved the production capability of replica optics in many areas.

1.5.1 Production Process

1. A relatively simple process is available for producing replica optics.

2. The equipment required for plastic replication is readily available. The personnel experience necessary for economical production may be difficult to acquire by those organizations with no previous replication experience.

1.5.2 Masters

1. Glass masters can be used at a small cost per replica. For aspherics, plastic submasters are recommended and appear economically feasible.

2. Metal masters are highly durable but cannot achieve the surface finish of glass masters.

1.5.3 Preforms

1. Spherical preforms can be machined from various common metals and meet the shock environment resistance requirements.

2. Reduced preform costs can be achieved using cast preforms.

1.5.4 Adhesive

1. The EPON 829 and DEAPA resin system will satisfactorily produce high-quality replicas.

2. Flexible epoxies and polyurethane resins offer higher mar resistance and durability for submasters and some replica environments.

1.5.5 Coatings

1. Post coating baking improves the adhesion of vacuum-deposited layers on plastic. Also an initial chromium coating enhances adhesion.

2. Chromium and silicon monoxide coatings enhance the replica resistance to humidity and salt spray.

1.5.6 Fixtures

Cosmetic voids and many master attrition difficulties can be eliminated with accurate fixtures and tooling.

1.5.7 Replicas

The replication process has developed to the point where consistent surface accuracies and cosmetic qualities can now be attained.

1.5.8 Optical and Environmental

1. Spherical replica mirrors of high quality and accuracy for energy focusing applications can be made easily. Aspherics should present no difficulties by using the same techniques employed in the fabrication of spherical replicas during this program.

2. Limited environmental tests indicate that the replicas should withstand standard fire control temperature cycling, shock, humidity, and salt spray environmental tests.

1.6 Recommendations

Based on this program, several recommendations for the future development of the process are indicated.

1. The thin-film high accuracy casting replication technique should be designed into a current reflective optic system or component requirement.

2. Extensive field use and storage of replica elements should be initiated for an accurate evaluation of replica optics. Only by a production test of this process can the true economics of high accuracy replication be demonstrated.

3. Additional vacuum coating development would improve the abrasion and environmental resistance of replicas and submasters.

4. Detailed analysis of replica corner prism preforms made since the program ended indicates that additional work on modifying preform fabrication tooling will improve replica accuracy appreciably.

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1-3   D. E. Kline and J. H. Saxton, "Radiation, Moisture, and Temperature Effects in Filled Epoxy Replica Flat Mirrors," Journal of the Optical Society of America, 51, 447 (1961)

1-4   Singer Manufacturing Company, "Investigation of Plastic Replica Mirror Optical Components," Contract DA-19-020-ORD-5237

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1-6   G. Hass and W. W. Erbe, "Method for Producing Replica Mirrors with High Quality Surfaces," Journal of the Optical Society of America, 44, 669 (1954)

1-7   A. P. Bradford, W. W. Erbe, and G. Hass, "Two-Step Method for Producing Replica Mirrors with Epoxy Resins," Journal of the Optical Society of America, 49, 990 (1959)

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1-9   U.S. Patent 2,464,738, J. U. White, et al., March 15, 1949

2. ANALYSIS AND THEORY OF THIN PLASTIC REPLICATION

All replication processes that do not involve post replication finishing to improve specularity, employ a polished master or submaster onto which the replica optical surface is formed by casting, molding, deposition, etc. All currently used methods involve processes that can and normally do involve strain which tends to distort the replica after it is parted from the master or submaster. In the thin-film plastic replication process discussed in this report, the plastic strains are minimized by the following factors:

1. Minimizing the plastic layer thickness.
2. Minimizing the plastic strain for a given thickness by using the optimum plastic properties.
3. Employing a preform with high rigidity.

The analysis given in Appendix A describes the effects of the above factors in the replication of flat, spherical, and paraboloidal mirrors. The conclusions are described below.

2.1 Plastic Layer Thickness

The preform rigidity is directly proportional to the plastic thickness. Typically a 0.0005 to 0.004 inch thickness is desirable.

The plastic thickness uniformity, which is a function of the preform accuracy and surface finish, should be typically between 0.0005 to 0.002 inch maximum to achieve 1/4λ (wavelength) accuracy at 5,461Å. The exact maximum depends on many factors including:

1. Cure shrinkage
2. Cure temperature
3. Plastic thermal expansion coefficient
4. Preform thermal expansion coefficient
5. Environmental temperatures

2.2 Plastic Strain

Plastic strain or shrinkage depends on the properties of the
n system used. Generally low temperature curing epoxies are most
rable. Fillers are not desirable since they degrade the surface
ularity.

2.3 Preform Rigidity

Preform rigidity is determined by the plastic strain, thick-
, and modulus of elasticity. High rigidity is achieved by using
k sections of high modulus materials. For maximum rigidity-to-
ht ratios, structures of beryllium, aluminum, glass, and magnesium
desirable. Also honeycomb and ribbed construction will give high
dity-to-weight ratios. Typically, a diameter to thickness ratio
en 6 to 8 is adequate for optics up to 6 inches in diameter.

3. REPLICATION PROCESS DESCRIPTION

Many optical elements can be generated and checked easily as either a concave or convex surface. Concave paraboloids and convex or solid corner prisms are relatively easy to make. Since a convex paraboloid and a concave or hollow corner prism are difficult to make, the most economical production of replica concave paraboloids and external reflecting prisms would probably require a double replication process as shown schematically in Fig. 3-1.

The process flow diagram is shown in Fig. 3-2. Each major process item is given a unit number. Each process task is indicated by a decimal. For convenience, the process description is described in Appendix B, where the process items and tasks are discussed by their respective numbers.
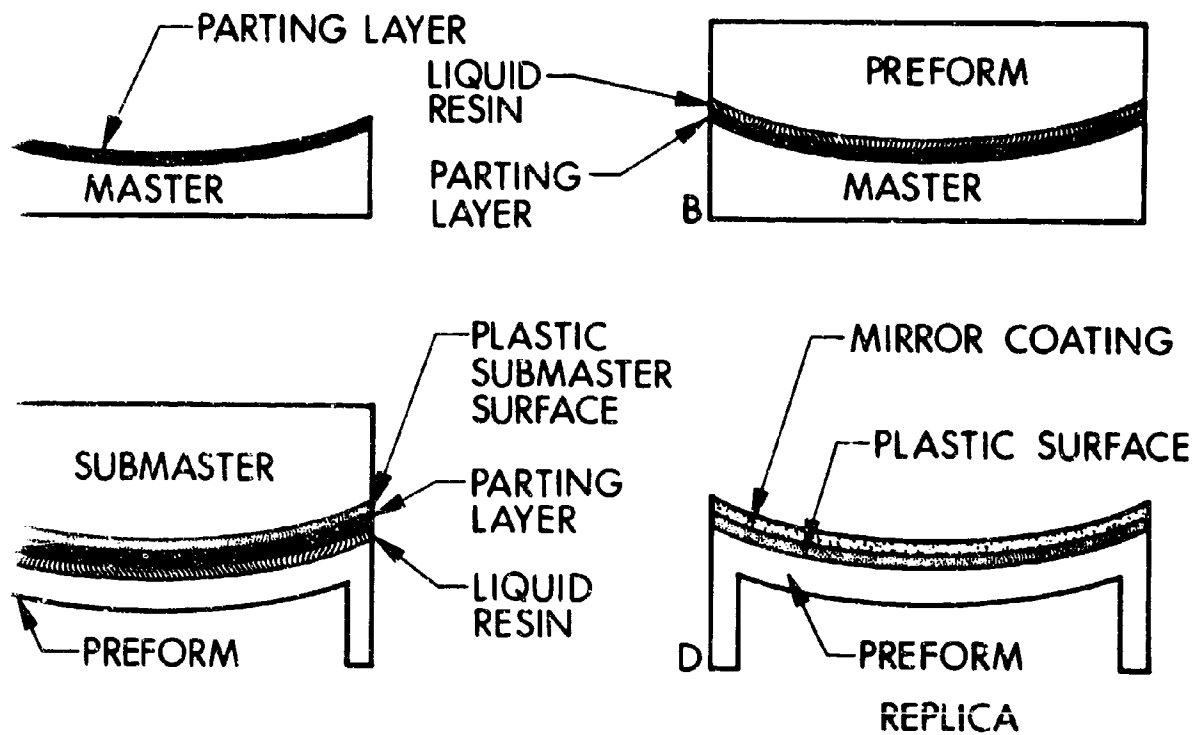
3-1 PLASTIC REPLICATION PROCESS

REPLICATION PROCESS FLOW DIAGRAM
(CONCAVE MASTER)

MAJOR PROCESS ITEMS

TASK	1. Master	2. Preform, Submaster	3. Replication, Submaster	4. Submaster	5. Preform	6. Replication, Final	7. Replica
.1 Procurement / Parting	1.1	2.1	3.5	4.1	5.1	6.5	7.1
.2 Receiving / In Process Inspection	1.2	2.2	3.6	4.2	5.2	6.6	7.2
.3 Cleaning	1.3	2.3	3.7	4.3	5.3	6.7	7.3
.4 Coating	1.4		3.8	4.4		6.8	7.4
.5 Plastic Preparation							7.6
.6 Plastic Application							7.9
.7 Joining or Layup							
.8 Curing							7.10
.9 Final Inspection							
.10 Packaging—Shipment/Storage							
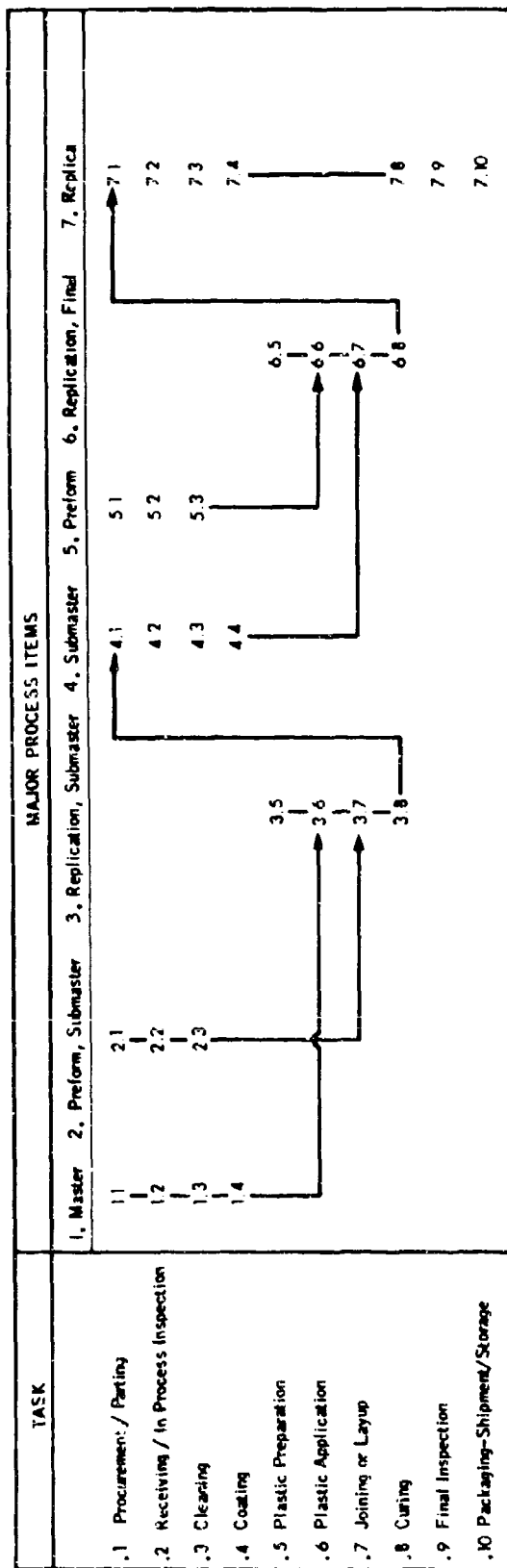
Note: With a convex master the sequence would go 1.4 ⟶ 3.7; 2.3 ⟶ 3.6; 4.4 ⟶ 6.6; 5.3 ⟶ 6.7

FIG. 3-2 REPLICATION PROCESS FLOW DIAGRAM

4. MASTERS

The master is a critical element in the replication process since replication economics and accuracies are highly dependent on master cost, design, materials, and attrition. Master requirements and considerations applicable to the fabrication of hollow replica corner prisms and spherical replicas are also adaptable to other types of replica optical elements.

4.1 Master Procurement

4.1.1 Fused Silica Corner Prisms

Five fused silica trihedral replica masters were originally ordered, four with a cumulative trihedral angular error of less than 4 seconds each and one with a cumulative trihedral angular error of 2 seconds. The order for these prisms was cancelled at no cost when the program was redirected.

Fused silica masters should produce more accurate replicas than BSC-2 type glass masters since the thermal distortion and coefficient of expansion of silica masters is low compared with BSC-2. Other properties of fused silica such as high hardness, chemical purity and high softening temperature enhance its superiority as a master material. Experience with fused silica on another replication program confirms these assumptions.

4.1.2 Metal Corner Prisms

Based on previous grinding and polishing studies of six types of flat metal masters, quotation requests were generated for the following types of metal masters:

1. 440 stainless

2. Chromium plated 440 stainless

3. HE grade tungsten carbide

One 440 stainless master was ordered but never used.

4.1.3 Spherical Masters

One concave green glass master 4 inches in diameter with an 8.4 inch radius of curvature was obtained from Frankford Arsenal.

Two convex BSC-2 glass masters 5 inches in diameter with an 8.4 inch radius of curvature were fabricated in the EOS shop together with a matching concave BSC-2 glass master having a diameter of 5 inches. These are now being used in replication studies. The initial replications were made with existing spherical masters having a radius of curvature of 14.188 inches.

A Ronchigram of the matching concave master is shown in Fig. 4-1. A discussion of the Ronchi test is given in Section 10.

Based on Rochi interferometric and visual tests, the masters were made to 1/4 wavelength accuracy and an approximate dig and scratch surface finish of less than 60-40.

4.2 Submasters

4.2.1 Replica Corner Prisms

Two plastic replica corner prism submasters were made using hollow replica corner prisms as masters and reject BSC-2 glass prisms as preforms. The fabrication of these submasters indicated that the bonding of the plastic to glass was poor and that release of the submaster sides from the master would have to be improved.

The effort on corner prism submasters was stopped when the program was redirected.

4.2.2 Spherical Submasters

Seven aluminum backed plastic surfaced convex replica masters were fabricated, (see Table 4-I). One master was made using the Frankford Arsenal master, five were made from the EOS-made concave test plate, and one was made from a replica.
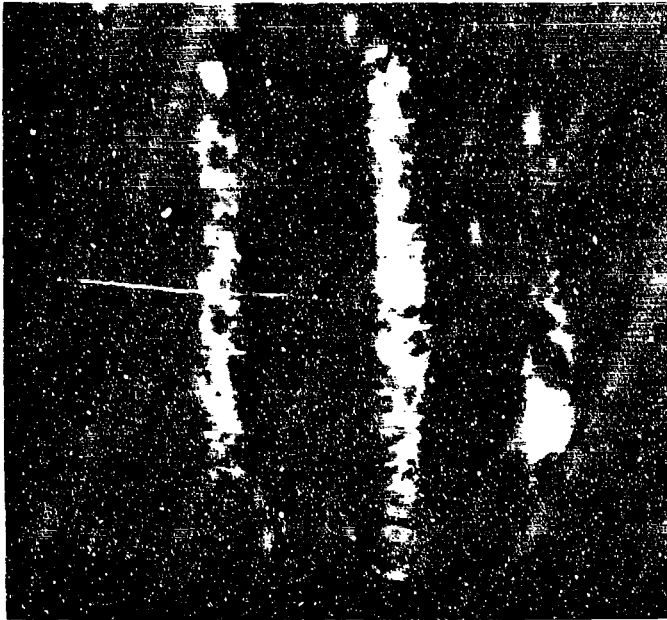
FIG. 4-1   8.4 INCH RADIUS OF CURVATURE
           SPHERICAL TEST PLATE.
           175 LINES/INCH RONCHI SCREEN
           Note: Over half the error
           shown is due to the tester
           beam splitter

TABLE 4-1

SUBMASTER REPLICATION SUMMARY

Sample Number	Date	Preform Type	Master Type	Coating	Resin	Hardener/PHR	Curing Cycle, temp/hrs	Replica Surface Quality	Remarks
1	7/6	Al	F	Al	828	DEAPA/9	110/15 + 140/1	Good	Replica surface coating split during parting due to master fracture
2	7/22	Al	G	Al	828	DEAPA/9	110/15 + 175/2	Fair	Resin flow marks / Produced in replica
3	8/21	Al	C	Cu	828	DEAPA/10	110/64	Fair	Replica full of bubbles
4	8/24	Al	C	Cu	828	DEAPA/10	125/15 + 175/1	Good	Plastic film of replica delaminated from preform while attempting to strip the Cu coating
5	8/25	Al	C	Cu	828	DEAPA/10	110/64	Poor	Cu stripped without delamination as in sample 4 above
6	8/31	Al	G	Cu	828	DEAPA/10	110/15 + 175/1	Fair	Master fractured during cure cycle
7	9/11	Al	Replica 39	Ag	828	DEAPA/10	110/64	Excellent	Replica used as master was ruined during parting

NOTES:

1. Sample number sequence starts with the beginning of the current program.
2. All dates are in 1964.
3. Al refers to convex machined aluminum preforms.
4. F is the Frankford concave master, C is the EOS concave master, 39 is replica No. 39.
5. Coatings Cu = vacuum deposited copper; Al = vacuum deposited aluminum.
6. Adhesive resin 828 refers to Shell EPON 828 resin.
7. DEAPA refers to diethyl aminopropylamine; (PHR) refers to the parts by weight of hardening agent added per 100 parts of resin.
8. Reflector surface quality: Excellent refers o very good surface quality; good refers to acceptable surface quality; fair refers to minor surface defects; poor refers to gross surface defects.
9. Parting Method: Parting with a fixture.

Thermal stresses caused by waxing the Frankford master to a backing plate prior to parting caused the master to fracture cleanly across the diameter. Aside from the hairline crack, the surface accuracy of the submaster was good.

Benchigrams of replicas made from this submaster are shown and discussed in Section 9.

The Frankford master was the same diameter as the desired finished replica which made submastering difficult. Ideally, the submaster should be between 1/4 and 1/2 inch smaller than the master and the replica should be between 1/4 to 1/2 inch smaller than the submaster. This size difference reduces mounting and alignment problems.

Most of the submasters were made with improper cooling. Many of the cosmetic difficulties encountered on the first six submasters were due to lack of control in joining the master and preform. More sophisticated tooling improved the submaster surface quality appreciably as demonstrated by the number 7 submaster. This tooling is discussed in Section 8. Improvement in the master life should occur with further tooling refinements. One of the major reasons why master life in the submaster fabrication has not improved more is that only limited time has been spent on this phase of the replica process.

4.3 **Master Life**

4.3.1 **Corner Prism Masters**

Insufficient data is available to predict the expected master life of a corner prism master. On another program, silica flat masters have been replicated over 70 times. In the replication of corner prisms, master life is highly dependent on master alignment.

Previous master alignment had been on a manual-gravity basis using the fluid plastic as a viscous lubricant. While expedient in prior development, this approach may have accounted for some of the master degradation reported. Alignment is particularly

important in corner prism replication or any other sharp edged, replica
optic which is not a surface of revolution since small misalignments
can cause preform and master contact. The improved alignment fixtures
used in the final spherical replications would probably increase corner
prism master life considerably. Experience indicates that metal masters
will give long master life.

4.3.2 Spherical Masters

Experience of the life of convex spherical masters has
been quite good. One of the EOS masters was replicated 28 times with
no detectable change in figure and only minor surface damage. Surface
damage consisted of several scratches and pits and two small edge cracks.
Most surface damage occurred during cleaning procedures and in handling.
Both the Kanigen and BSC-2 6 inch diameter 14.188 inch radius of cur-
vature masters initially used were used in a total of over 20 replications
each without loss of figure. The BSC-2 glass master had a hairline
crack before it was used on this program. This crack was the point of
fracture when the master broke. Masters held in storage at approximately
$74^{\circ}F$ and 50 percent humidity for periods up to four months showed no
observable attrition.

5. PREFORM

In the replication process, the preform is a major factor in determining the stability, environmental resistance, angular accuracy, reflective surface finish, and cost of the finished replica optic. Therefore, the successful adaptation the art of replication to production optics depends on the selection of optimum preform fabrication methods amenable to low cost automatic production techniques.

5.1 Hollow Corner Prism Preforms

The preforms used in the replication of hollow replica corner prisms were made on the previous contract (DA-04-495-AMC-51(A)) of die cast aluminum alloy number 380. These are shown in Fig. 5-1. Detailed analysis of the accuracy of replica prisms indicated that these preforms had angular errors of about 60 seconds which limited the ultimate obtainable accuracy. Also the faces of each preform were about 0.001 inch concave due to the contraction of the preform upon cooling immediately after die casting.

The angularity difficulties were probably attributable to errors in the die fabrication. These errors were considerably reduced when the die mold was repaired early in the program. However, the die was never run since the program was redirected to make spherical replicas.

Improved tooling was developed to gage the flatness and angular accuracies of the preforms.

5.2 Spherical Preforms

Thirty six machined spherical preforms were made from the following materials:

1. 2024 aluminum (16 total)
2. 4340 steel (4 total)
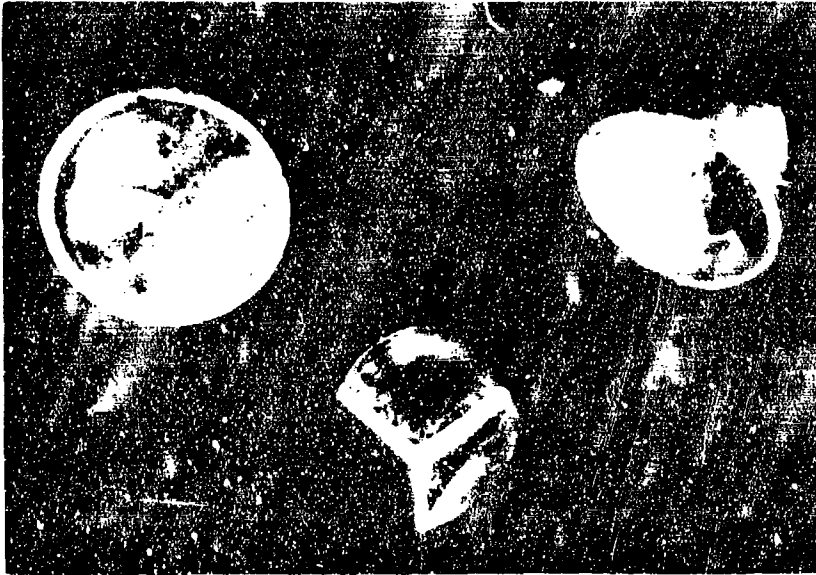
FIG. 5-1   DIE CAST PREFORMS

3. 416 stainless steel (4 total)

4. AZ31B magnesium tooling plate (8 total)

5. 6Al-4Va-titanium (4 total)

Three of the four various alternate preform constructions are shown in Fig. 5-2. The fourth alternate design is similar to alternate A except it has no lightening holes counterbored in the preform back. For future reference, this alternate shall be designated as alternate D. The initial preforms used a 14.188 inch radius preform instead of the 8.4 inch preform. These various alternates in preform design were chosen to determine the effect of the structural design on the shock resistance.

The number of spherical replicas required on the revised program did not warrant the fabrication of casting or molding tooling.

Aluminum and magnesium preforms were initially lap ground to a 3F finish. The purpose of the lap grinding was to increase the accuracy of the preform, reduce surface roughness, and provide a surface which would yield greater adhesion of the epoxy film. Subsequent experience indicated that the lap grinding was unnecessary. In fact, it was demonstrated that replica surfaces were superior when the preforms were not ground. The reason for the surface improvement is not well understood. However, it is felt that the rough surface allows air entrapment and bubbles result as the air expands during the curing cycle.

Preforms of poor replicas were reused. These preforms offered a variety of surfaces for layup. Where previously deposited epoxy was mechanically removed, the preform often had numerous scratches too deep to remove readily by lap grinding. Layup on these surfaces gave good results except in the case where epoxy films were one thousandth of an inch thick or less. In these cases, the defects in the preform surface telegraphed through the epoxy film.

Several layups were made directly on previously deposited epoxy. The resultant replicas had good surfaces, but they were often delaminated.

.875 -.010

.90±.01
(DEPTH OF 1 1/2 DIA. HOLES)

8.40 SPHERICAL RADIUS

4.25 SPHERICAL RADIUS

4.249 -.002

4.00 +.01

4.00 +.01

.238 (REF.)

A

1.25 — 1.25

1.25

1.25

1 1/2 DIA. TO DEPTH SHOWN

.187

.187

B

C
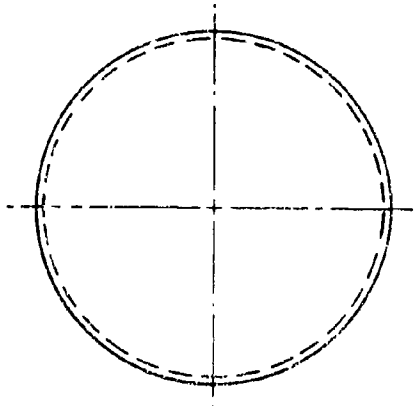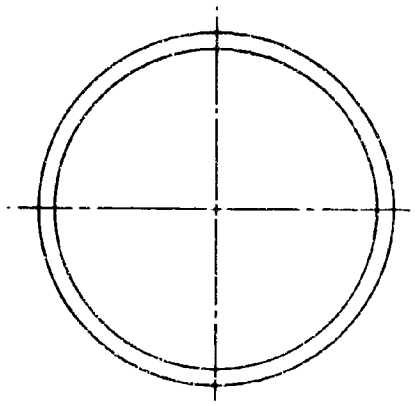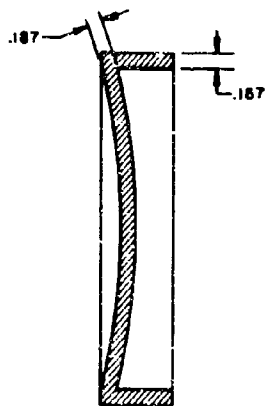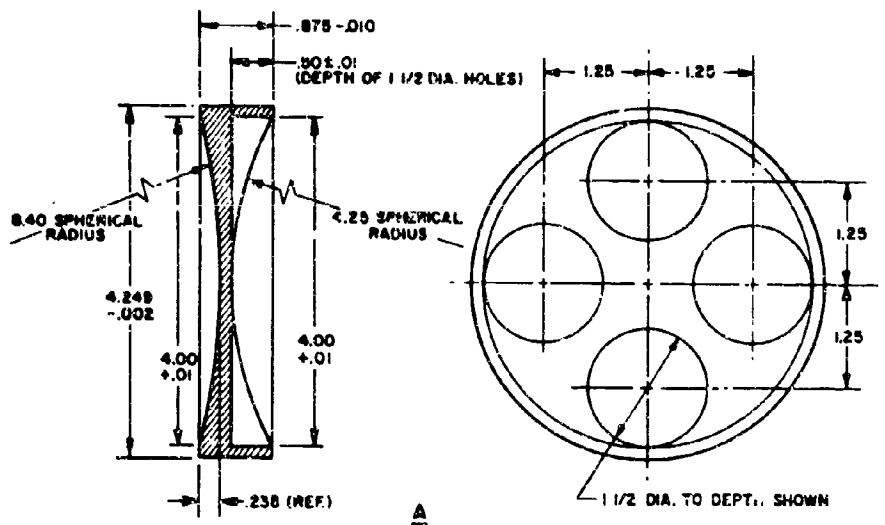
NOTES:
FINISH 125/ ALL OVER
BREAK ALL SHARP EDGES
DIMENSIONS FOR ALTERNATES B & C ARE THE SAME AS ALTERNATE A, EXCEPT AS NOTED

TOLERANCES: DECIMALS ±.010
FRACTIONS ±1/64
ANGLES ±2°

FIG. 5-2   PREFORM ALTERNATES

6. PLASTIC RESINS

The plastic resin is probably the most critical element in the replication process. Significant advances in the application and analysis of adhesive characteristics in the replication process were made in the previous programs. However, further improvements in adhesive characteristics would result in a direct and proportional improvement in replica characteristics.

6.1 Systems

6.1.1 Epoxies

Overall experience, up to now, indicates that replicas made with standard rigid bisphenol A type epoxy resins have highly satisfactory properties for meeting practically all optical, mechanical, thermal and environmental stability requirements. This type resin is represented by Epon 828 (Ref. 6-1).

When considering the economically important production of suitable submasters, it is believed that the rigid type epoxy surface may be too brittle to withstand the required cleaning treatments and to allow repetitive replication in large numbers. Elastomeric type polymers should offer decided advantages for this application.

Chemical resistance of bisphenol A type resin cured with polyfunctional aliphatic ammer, such as EPAP, are listed in Table 6-1. The test samples, 1 x 3 x 1/8", were cured at room temperature for 3 weeks. The weight gain expressed in percent absorption was determined on samples submerged for various periods of time in each respective liquid chemical or solvent.

6.1.2 Resilient and Flexibilized Epoxies

Limited tests have been conducted in evaluating available resilient and flexible epoxy resins. Two such types, both obtainable from the same source (Ref. 6-2) are briefly discussed, as follows:

TABLE 6-1

Chemical Resistance of Unfilled, Amine-cured

Bis-phenol A Type Epoxy Resins

REAGENTS	1 Day	1 Week	1 Month	3 Months
Inorganic acids				
25% Sulfuric	0.40	0.96	2.05	3.83
15% Hydrochloric	0.22	0.61	1.25	2.20
5% Nitric	0.25	0.65	1.41	2.37
10% Phosphoric	0.57	1.75	2.98	5.27
Organic acids				
25% Acetic	4.94	12.74	(1)	...
5% Acetic	0.72	1.35	2.96	5.47
25% Lactic	2.01	5.15	9.67	27.54
5% Lactic	0.43	1.15	2.01	2.93
Oxalic (sat.)	0.62	1.46	3.01	5.99
Alkalies and detergents				
15% Sodium hydroxide	0.13	0.35	0.71	1.19
5% Sodium hydroxide	0.15	0.41	0.85	1.45
28% Ammonium hydroxide	0.28	0.51	0.92	1.60
5% Detergent	0.16	0.42	0.86	1.49
Oxidizing agents				
10% Sodium hypochlorite	0.13	0.30	1.57	1.04
Mild Solvents				
Water	0.16	0.45	0.90	1.58
Transformer oil	0.04	0.05	0.08	0.09
Strong solvents				
Methylene chloride	(1)	...	...	...
Methyl ethyl ketone	2.35	7.61	15.11	20.96
o-Dichlorobenzene	0.38	1.06	2.17	3.19
Toluene	0.26	0.77	1.46	2.37
Trichloroethylene	(1)	...	...	...
Ethanol	0.42	0.84	1.31	1.75

(1) Sample disintegrated

*Data taken from paper by H. G. Cooke, et al., "Chemical resistance of Epoxy Resins" ...

6.1.2.1 Epotuf 37-134

Epotuf 37-134 cures to a polymer of relatively high resiliency. The literature discloses that this property makes possible practically stress-free coatings. Formulation and cure cycle suggested by the manufacturer are:

Resin: Epotuf 37-134	100 parts by weight
Hardener: Triethylenotetramine	10 parts by weight
Cure at room temperature (77°F)	24 hours
Post cure at 150°F	2 hours
Potlife at room temperature	4 - 6 hours

Initial tests showed that the suggested hardener is not compatible with the resin when centrifuging for removal of entrained air. However, it was found that this could be corrected by allowing the hand-mixed compound to stand for approximately 1 hour prior to centrifuging. The cured resin coating is extremely tough and resilient.

6.1.2.2 Epotuf 37-151

Epotuf 37-151 cures to a flexible polymer. It is not useable in this application except as a flexibilizer in combination with standard rigid type epoxy resins, such as Epotuf 37-140. The suggested hardener is aminoethylpiperazine.

Various evaluation tests were conducted, using different ratios of Epotuf 37-151 to 37-140 and varying curing cycles. The suggested hardener was also found to be incompatible with the resins, when centrifuging. This difficulty could not be solved.

The results of these preliminary studies were not sufficiently promising to continue this investigation.

6.1.3 Polyurethanes

Polyurethane elastomers are definitely considered as potentially superior materials for submasters. Various formulations

composed of urethane prepolymers, polyols, polyethers, and catalysts, have been evaluated to a limited extent. The principal problem has been that of eliminating bubble formation during layup and cure. This has, so far, not been solved to complete satisfaction. Bubble formation is probably connected with the reactivity of isocyanate groups of the prepolymers with traces of water. The byproduct of this reaction is carbon dioxide:

$$R \cdot NCO + H_2O \rightarrow RNH_2 + CO_2$$
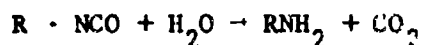
The following basic chemical reactions illustrate the mechanism by which polyurethanes are obtained. The first step yields a urethane prepolymer by reaction 2 moles of di-isocyanate with 1 mole of a polyfunctional hydroxy compound, such as glycols, glycerols, etc.

$$2\ OCN-R-NCO + HO-R'-OH \rightarrow OCN-R-\overset{H}{\underset{|}{N}}-\overset{O}{\underset{\|}{C}}-O-R'-O-\overset{O}{\underset{\|}{C}}-R-NCO$$

or

$$n\ OCN-R-NCO + R'(OH)_n \rightarrow R'(O-\overset{O}{\underset{\|}{C}}-\overset{H}{\underset{|}{N}}-R-NCO)_n$$
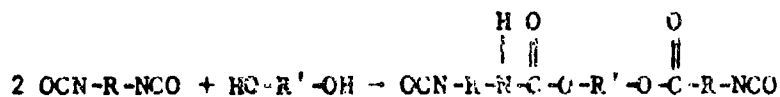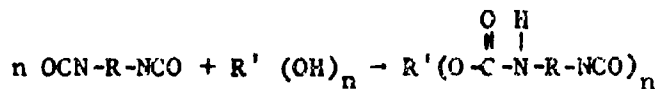
The reaction product is a liquid polymer of moderate molecular weight with an excess of isocyanate groups. This is known as a prepolymer. It can still react with additional hydroxy or amino groups. However, the reactivity is relatively mild which facilitates handling and control of the mixture during layup and cure.

This prepolymer is mixed with a polyol or an amino in presence or without a catalyst. The cured end product is an elastomer of widely modifiable flexibility, surface hardness and other physical properties.

The prepolymers are commercially available in form of viscous liquids. Polyols and amines are also readily obtainable from a number of chemical manufacturers. Catalysts are special types of amines or certain metal-organics. (Ref. 6-3).

Prior to mixing the prepolymer and any of the indicated

tants, it is advisable to briefly expose each separately to a vacuum

from 2-5 mm mercury pressure at 25° to 150°F to assure complete

oval of low boiling contaminants, water and air. After mixing by

d, the compound is degased by centrifuging. Resin mixture, pre-

n and master are preferably heated to a temperature sufficiently

h to remove any adsorbed water or air. However, care has to be

rcised to prevent premature gelling.

A typical representative example of a urethane formula-

n and its processing for replication purposes is as follows:

hane prepolymer	Adiprene L-100	100 pts by weight
ne catalyst	MOCA	11 pts by weight
ing temperatures	212°F	
life at 212°F	15 minutes	
time at 212°F	25 minutes	
at 212°F	3 hours	
cure at room temp.	7 - 14 days	

The Adiprene L-100 is heated to 212°F and degased for

minutes at a pressure of 5 mm of mercury. The curing agent MOCA is

added as a liquid. MOCA is a solid at room temperature, but melts

kly to a low viscosity liquid at 250°F. The ingredients are mixed

and stirring for 2 minutes and centrifuged for 2 minutes at 2,000

. The mixture is then poured onto a preform for standard layup with

ster and heat cured for 3 hours at 212°F.

Adiprene-L-100

Viscosity at 86°F	14,000-19,000 cps
Viscosity at 212°F	500-600 cps
Storage stability	Excellent at room temperature, in absence of moisture

MOCA

4,4'-methylene-bis- (2 chloroaniline)

Solid at room temperature

Melting range	212 - 220°F
Storage Stability	Excellent - slightly hydroscopic

Properties of Cured Polyurethane Elastomer

Modulus at 300 percent, psi	2,100
Tensile strength, psi	4,500
Elongation break, percent	440
Hardness, Shore A	90
Brittleness test, $-80^{\circ}F$	No break

Adiprene L-100 elastomers have good oil and solvent resistance. Aromatic and polar solvents cause moderate to severe swelling:

Percent Volume Increase, 14 days at $158^{\circ}F$

Immersion in:

ASTM #1 Oil	-5
ASTM #3 Oil	18
SAE #10 Oil	4
Isooctane	14
n-Hexane ($75^{\circ}F$)	17
Acetone ($75^{\circ}F$)	74
Amyl acetate	94
Carbon tetrachloride	120
Toluene	124
Benzene	134
Methyl ethyl ketone	348

Percent Volume Increase, 40 days at $75^{\circ}F$

Immersion in:

20 percent Hydrochloric acid	8
50 percent Sulfuric acid	dissolved, 4 days
20 percent Acetic acid	12
50 percent Sodium hydroxide	1
20 percent Nitric acid	dissolved
100 percent Ammonium hydroxide	2

The urethane prepolymers are compatible with liquid epoxy resins (Shell Epon 828) in all proportions and function, therefore, as excellent flexibilizers for them. Addition of Adiprene L-100 reduces the brittle point and increases impact strength and mar resistance of the cured resin. Variations in ratio of Adiprene L-100 to epoxy resin produce elastomers having a range of hardness from 65 Shore A to 85 Shore D. These compositions have a smooth glasslike surface of very low friction.

Experimental studies have been, so far, conducted with the above mixtures of Adiprene L-100 and MOCA. In addition, 5 resin formulations, suggested by the Baker Oil Company, have also been investigated. These make use of polyols in place of amines. Other materials and formulations will be tested which will be supplied by Naugotuck Chemical Co., and Monsanto Chemical Company.

As a result of this experimentation, it was found that these same urethane prepolymers, admixed and cured with amines or polyols, are excellent adhesives. Their peel strength is far superior to that of epoxy resin adhesives and of various unidentified commercial adhesives recommended for this purpose. High environmental stability ($+165^{\circ}$F to -70°F; 100 percent R.H.) was also established.

6.2 Shelf Life

The shelf life of bisphenol A type epoxy resins at room temperature is excellent (> 1 year). This is also true for the hardener DEAPA. However, DEAPA is hygroscopic and should, therefore, be protected in storage against contact with moisture. Potlife of the resin-hardener mixture at room temperature is between 2-4 hours, when using DEAPA up to 10 parts per HPR.

REFERENCES

Section 6

6-1 Shell Chemical Co., 10642 S. Downey Street, Downey, California

E. V. Roberts & Associates, Inc., 3813 Hoke Avenue, Culver City, California

6-2 Reichhold Chemical Co., 237 S. Motor Avenue, Azusa, California

6-3 Urethane prepolymers:

DuPont, Elastomer Chemical Department, Wilmington 98, Delaware (Tradename: Adiprene)

Baker Castor Oil Co., Bayonne, New Jersey, (Tradename: Polycine U-56 and U-63)

Naugatuck Chemical Co., Naugatuck, Connecticut, (Tradename: Vibrathane)

Polyols and Polyethers

Baker Castor Oil Co., Bayonne, New Jersey
Union Carbide Chemicals Division, 270 Park Avenue, New York City, New York
Dow Chemical Co., Midland, Michigan

Catalysts (Amines and metal organics)

DuPont Elastomer Chemical Dept., Wilmington, Delaware

Naugatuck Chemical Co., Naugatuck, Connecticut

M & T Chemicals Co., Rahway, New Jersey

Houdry Process Corporation, 1528 Walnut Street, Philadelphia 2, Pennsylvania

7. COATINGS

The coating problems associated with replica optics are comparable with those of conventional optics with one exception; the use of a release coating. References 1-1 through 1-9 cover the range of release coatings applicable to replica optics. Since the actual coating process is described in the Replica Process Description, only the experimental results and conclusions are given here.

7.1 Release Coatings

Soft metal release coatings have been used with good success as master release coatings. In order of preference they are:

1. Copper
2. Silver
3. Gold
4. Aluminum

On another program, soft copper release layers were used over 80 times on a master before fracture occurred.

It is possible that some of the previous master attrition attributable to poor release coatings may have been due either to increasing master roughness or to the gradual diffusion of the release coating metal into the glass. Roughness and diffused metal would help promote a stronger bond at the release coating-glass interface.

Release coatings on metal masters are not as critical as on glass due to the lower water absorption of metal and the passive surface of most metal surfaces, which tends to act as a natural release layer by itself.

7.2 Mirror Coating Adhesion

Several successful methods of improving mirror coating adhesion have been investigated.

7.2.1 Predeposition of Mirror Coatings

Reflective vacuum coatings applied to the master and transferred during replication have higher adhesion than post replication deposited coatings. The post replication coatings applied to the replica do not wet the cured plastic whereas the plastic monomer, prior to curing, wets the prereplication vacuum coatings. This wetting promotes a strong adhesive bond. These adhesive differences can be more accurately explained by comparing the relative surface-free energies of the vacuum coatings and liquid plastic monomer and the cured plastic and condensing vacuum coatings, respectively.

The plastic resin polymer has a much lower surface-free energy than condensing metal. In adhesion studies liquid materials with high surface-free energy do not adhere well to solid materials of low surface-free energy. Therefore, it is not surprising that metal-mirror films have only marginal adhesion when deposited over cured plastic resin. On the other hand, the plastic resin prepolymer has a very low surface-free energy with respect to mirror coatings predeposited on the master; this relationship promotes good adhesion. Therefore, mirror coatings, which are transferred from the master to the replica surface, have a much higher adhesion than postdeposited coatings. This adhesion approximates the tensile strength of the epoxy and has been repeatedly demonstrated. However, metal coatings alone are insufficient to withstand the humidity and salt spray requirements specified for military optics. The epoxy resin system used in the fabrication of most of the replicas is slightly affected by moisture, and requires a moisture barrier.

7.2.2 Post Baking

Post baking of vacuum deposited aluminum films is a standard method of improving the adhesion of aluminum to glass. The same technique applies to aluminum over plastic. Post baking is easily accomplished by baking the coated replica for 2 hours at 175°F. Post baked aluminum coated replicas will easily pass the standard tape test for vacuum coatings.

7.2.3 Adhesion Promoters

Vacuum deposited adhesion promoters will greatly improve the adhesion of the mirror coatings to the plastic resin. Excellent results have been achieved using an initial vacuum layer of chromium followed by successive layers of silicon monoxide, aluminum, and silicon monoxide. Of the coating systems used and investigated on this program, this combination gave the best results on adhesion, humidity, and salt spray tests.

7.3 Recommendations

Despite the theoretical reasons for predepositing mirror coatings, on the basis of the current state-of-the art post coating is recommended for applying vacuum mirror coatings to plastic replicas. This recommendation is based primarily on the inability to predeposit silicon monoxide coatings, which are necessary in most applications to give improved abrasion resistance.

Future coating work should be considered in the following areas:

1. Depositing silicon monoxide over gold
2. Depositing improved abrasion resistant coatings for submaster to increase submaster life
3. Additional environmental tests

8. FIXTURES AND TOOLING

8.1 Corner Prism

8.1.1 Die Cast Tooling

The prism punch and ejector pins of the die cast preform tooling, Fig. 8-1, were reworked to correct defects. This tooling was not used after rework due to the program reduction.

8.1.2 Vacuum Coating

Modifications were made to an 18 inch vacuum coating system to facilitate prism master rotation and multiple coating evaporation. The program redirection el 'nated the need for these fixtures.

8.1.3 Centrifuge

Adapter plates for the centrifuge were made to facilitate master cleaning. This tooling was also used with the spherical masters.

8.1.4 Preform Inspection Tools

A simple sphereometer gage was made to test the preform face flatness. Also, an angle gage was fabricated to check the perpendicularity between faces. The gages use a mechanical indicator readable to 0.00005 inch.

8.2 Spherical Replica Layup and Parting Fixtures

Initial layups were made by hand. Replicas produced with this method had a considerable number of resin voids due to bubbles being introduced into the resin during the layup. Layup fixtures (see Figs. 8-2, 8-3 and 8-4) were fabricated to aid in master coating, lowering into preforms, holding during curing, and parting. Greater control of these fixtures, particularly the arbor press,
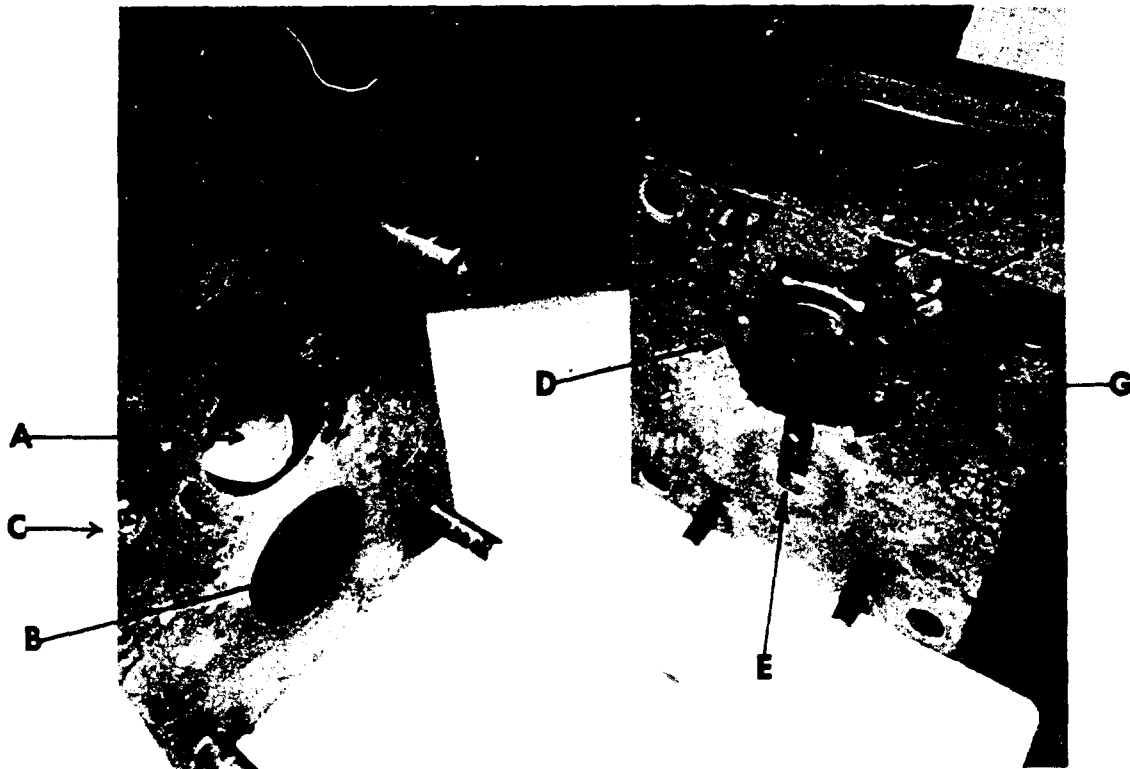
A. Die cavity

B. Aluminum injection cylinder

C. Alignment pins (4) between dies

D. Overflow cavities (3)

E. Inlet gate

F. Ejector pins (5)

G. Punch

FIG. 8-1 DIE CAST PREFORM TOOLING
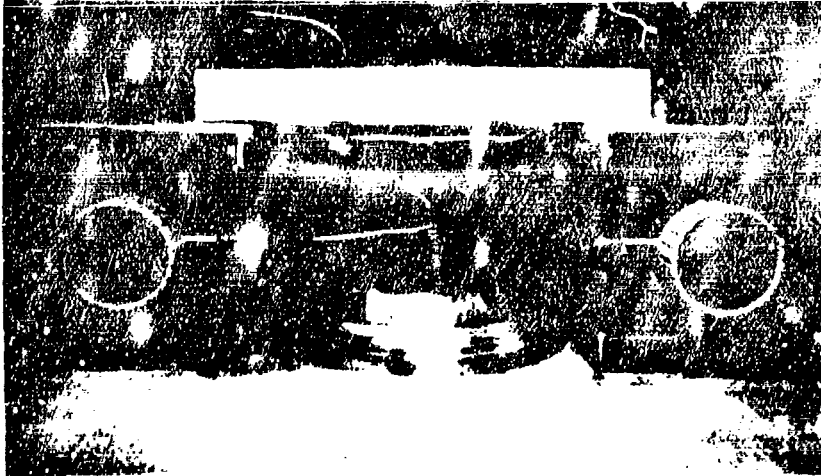
FIG. 8-2 LAB-JACK LAYUP FIXTURE
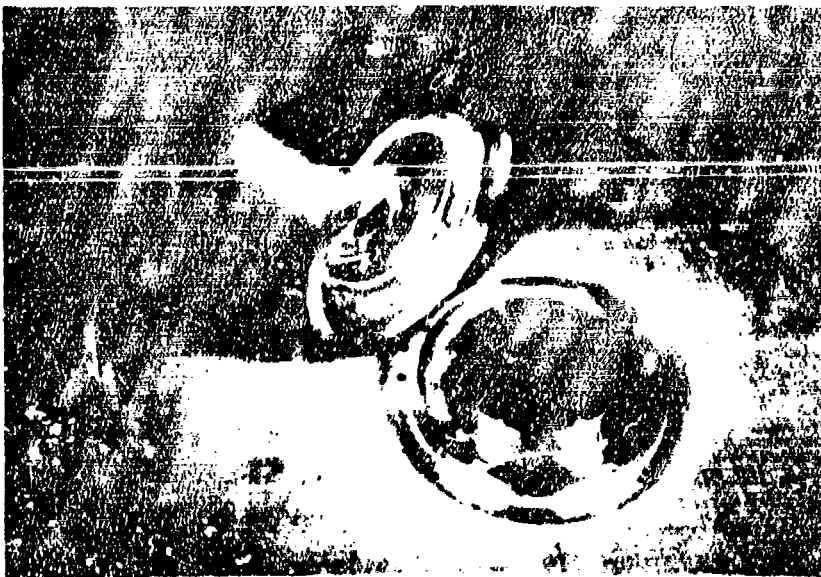
FIG. 8-3 CYLINDRICAL LAYUP AND PARTING FIXTURE
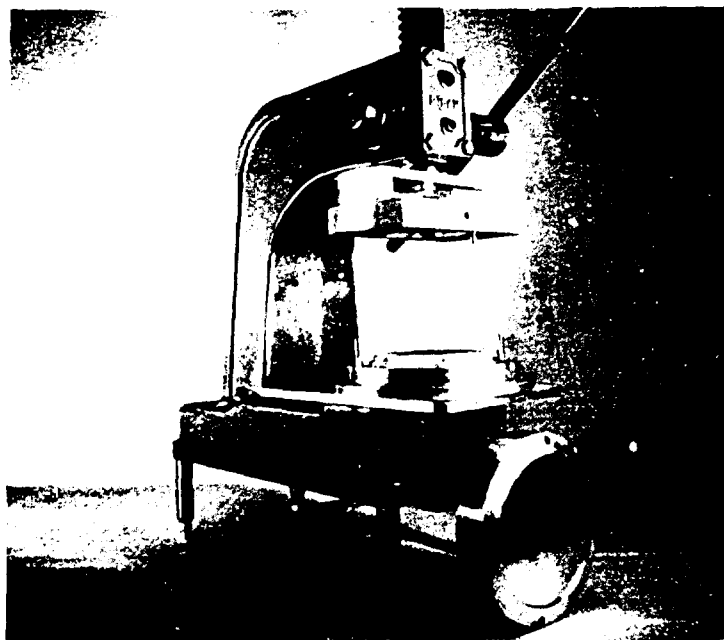
FIG. 8-4 MODIFIED ARBOR PRESS, STEP NUMBER ONE

FIG. 8-5 EARLY MODEL REPLICA PARTING FIXTURE

in the process of mating the master and preform has resulted in a significant drop in the occurrences of resin voids.

Problems of handling the master have been greatly reduced with the arbor press tooling. The master holding fixture was designed so that it mounts easily on the centrifuge, in the vacuum chamber, and on the arbor press without changing fixtures. Alignment during layup is achieved with indexing pins that are fixed to the base plate and engage the master holding fixtures. These indexing pins also serve to maintain alignment during the cure cycle.

Parting force applied to the layup must be exerted uniformly. Fixtures were fabricated that independently secured the master and the preform. Once the master and preform were secured, force could be applied to affect separation. Figs. 8-3, 8-4, and 8-5 show three different fixtures that were used for parting. Uniform parting force was achieved in Fig. 8-5 by alternately tightening the four 3/8-inch corner bolts. This fixture belonged to another program. A similar technique was used with the fixture illustrated in Fig. 8-3. Clockwise rotation of the rack gear lever pictured in Fig. 8-4 provides a uniform vertical pressure on the master while the preform is secured to the arbor press stage. This last fixture was the best parting and layup fixture.

The detailed operation of this fixture is described in the process description.

8.3 Optical Test Equipment

An improved tester was fabricated to test and photographically document the accuracy of very low f/rating replicas. This is shown in Fig. 10-1, and can be used as a knife-edge, single-wire Foucault or Ronchi tester. The tester uses the projection system of an optical bench.

9. REPLICA RESULTS

Since the replication process details are discussed elsewhere, this section deals primarily with replica results except where the process details illustrate a specific point relative to processing.

9.1 Corner Prism Replica Results

Prototype replicas are summarized in Table 9-I. These are not representative prototype production replicas because they served as training exercises for new program personnel. The masters used had been internally fractured in prior work and, with the exception of masters 417 and 422, were not within specification prior to replication. The masters are summarized in the final report of Contract DA-04-495-AMC-51A, which was the previous program. Replicas 4 and 6 were within the required 45 sec collimated light specification.

The vacuum aluminum coatings were post-deposited over plastic. However, the aluminum adhesion was poor. This problem initiated some of the coating adhesion studies, described in Section 7.

These initial corner prism replica results have indicated the necessity for better alignment and preform inspection. Tooling to accomplish the preform inspection was described previously. The alignment fixture now used with the spherical replicas can also be used with corner prisms with some modifications.

9.2 Spherical Replica Results

Figure 9-1 shows a typical spherical replica produced on this program. Table 9-II is a summary of spherical mirror replication.

9.2.1 Cosmetic Quality

The major difficulties in fabricating high quality replicas appear to be cosmetic. These are due largely to resin voids

TABLE 9-1

SUMMARY OF PROTOTYPE COARSE PRISM REPLICAS

Sample Number	Date	Preform Lot Number	Master Lot Number	Coating	Coating Quality	Adhesive Resin	Releasing Agent (PVA)	Relative Humidity (percent)	Alignment	Curing Cycle - Temp (°F)/Time (hrs)	Parting Method	Reflector Surface Quality	Implied Angles - 1:2 (seconds)	Deviation in - 1:3 (seconds)	Reflected ray - 2:3 (seconds)	Overall Deviation	Remarks
1	4/6	2,000	409	A1	Fair	828	DRAPA/9	48	Gravity	125/16	F	Fair	40	16	225	-	Scratched
2	4/9	2,001	409	A1	Fair	828	DRAPA/9	45	Gravity	75/16	F	Poor	60	160	270	-	Resin did not part
3	4/13	1,169	409	A1	Fair	828	DRAPA/9	47	Gravity	120/18	F	Poor				-	Master fractured
4	4/20	1,170	17	A1	Good	828	DRAPA/9	53	Gravity	122/15	F	Good	5	5	5	10	Master crack enlarged
5	4/21	1,161	22	A1	Good	828	DRAPA/9	53	Gravity	122/16	F	Poor	5	30	5	34	Resin fractured at apex
6	4/22	1,163	17	A1	Good	828	DRAPA/9	50	Gravity	122/16	F	Fair	5	10	5	30	Resin did not part uniformly
7	4/23	1,159	17	A1	Good	828	DRAPA/9	46	Gravity	122/16	F	Poor					Master did not part uniformly
8	4/23	1,152	16	A1	Good	828	DRAPA/9	46	Gravity	122/16	F	Poor					Master fractured
9	4/24	1,153	23	A4	Good	828	DRAPA/9	45	Gravity	122/64	F	Fair	40	5	45	90	Master fractured
10	4/29	1,167	25	A1	Good	828	DRAPA/9	47	Gravity	125/16	F	Good	45	5	30	75	Resin did not completely cover optical surface

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9.2 Spherical Replica Results

Figure 9-1 shows a typical spherical replica produced on this program. Table 9-II is a summary of spherical mirror replication.

9.2.1 Cosmetic Quality

The major difficulties in fabricating high quality replicas appear to be cosmetic. These are due largely to resin voids

TABLE 9-1 NOTES:

1. Sample number sequence starts with the beginning of the current program.

2. All dates are in 1964.

3. Preform log number refers to the number assigned to each preform. 1100 and up refers to die cast aluminum preforms.

4. Master log number refers to the number assigned to each master. The number sequence started in a previous program.

5. Coatings Ag = vacuum deposited silver; Al = vacuum deposited aluminum.

6. Coating Quality - good refers to vacuum deposited coatings free from visual defects; fair refers to vacuum deposited coatings with minor defects, but still acceptable for replica testing; good coatings would meet the coating requirements for MI reflectors.

7. Adhesive resin 828 refers to Shell EPON 828 resin.

8. DEAPA refers to diethyl aminopropylamine; (PHR) refers to the parts by weight of hardening agent added per 100 parts of resin.

9. Relative humidity is given in percent.

10. Gravity alignment refers to gravity alignment of the master with the replica after initial prealignment by the fixture or by hand.

11. Curing cycle: Temperature of cure/the total hours of cure.

12. Parting Method: F refers to the fixture described in the previous program.

13. Reflector surface quality. Good refers to acceptable surface quality; fair refers to minor surface defects; poor refers to gross surface defects.

14. Replica Angle Accuracy refers to the angle between faces marked on the replica preform. 1:2 refers to the angle between face 1 and face 2, etc. Faces are measured clockwise as viewed into the replica aperture. On the die cast preforms face 1 is the face opposite the inlet gate.

15. Overall Deviation refers to the deviation in the collimated beam as measured by a Penn Optical collimator calibrated to a 60 second collimated beam deviation per ruling. For deviations less than 60 seconds, the figures are good to ± 5 seconds accuracy. Readings over 60 seconds are good to ± 10 seconds accuracy. NR = not readable.

FIG. 9-1   SPHERICAL REPLICAS WITH LIGHTENED
ALUMINUM PREFORMS

TABLE 9-II

SPHERICAL MIRROR REPLICATION SUMMARY

Sample Number	Date	Preform Type	Master Type	Coating	Resin	Hardener/PBW	Parting Method	Cure Cycle, Temp/time	Replica Surface Quality	Deviation	Remarks
1	5/27	A1	Kanigen	Ag	828	DEAPA/9	Force	125/16	Fair	45"	Replica surface full of large bubbles; mirror slightly parabolic
2	5/27	A1	Glass	A1	828	DEAPA/9	Force	125/16	Fair	45"	Replica surface full of many bubbles; surface streaks evident
3	5/28	A1	Kanigen	Au	828	DEAPA/9	Force	125/87	Good	8-10"	Few surface bubbles; some zonal aberration
4	6/3	A1	Kanigen	Au	828	DEAPA/9	Force	125/15	Fair	5"	Numerous bubbles; very difficult to part; some zonal aberration
5	6/3	A1	Glass	Au	82?	DEAPA/9	Force	125/15	-	-	Master fractured during parting
6	6/5	A1	Kanigen	A1	828	DEAPA/9	Force	125/64	Good	< 4"	Numerous bubbles in replica surface
7	6/8	A1	Kanigen	A1	828	DEAPA/9	Force	125/15	Good	< 4"	Master mechanically lowered into preform during layup -- result, few bubbles
8	6/9	A1	Kanigen	A1	828	DEAPA/9	Force	125/15	Good	< 4"	Difficult to part; few surface bubbles
9	6/10	A1	Kanigen	A1	828	DEAPA/9	Force	125/60	Poor	< 4"	Almost entire replica surface covered with bubbles
10	6/1.	A1	Kanigen	A1	828	DEAPA/9	Force	125/16	Good	< 4"	Difficult to part; few surface bubbles
11	6/15	A1	Kanigen	A1	828	DEAPA/9	Force	125/15	Fair	< 4"	Two areas resin streaked; no center aberration
12	6/25	A1	A	Au	828	DEAPA/9	Force	125/15	Good	< 4"	Some local aberration
13	6/29	A1	A	Au	828	DEAPA/9	Force	125/15	Fair	< 4"	Numerous pits due to sputter marks
14	6/30	Mg	A	Au	828	DEAPA/9	Force	125/15	Fair	"	Surface has mottled appearance from lab jack lowering
15	7/1	Mg	A	Au	828	DEAPA/9	Force	100/15 + 140/3	Fair	< 4"	Many sputter marks
16	7/7	Mg	A	Au	828	DEAPA/9	Force	110/15 + 175/1	Fair	< 4"	Splits in Au coating on replica

TABLE 9-II (contd)
SPHERICAL MIRROR REPLICATION SUMMARY

Sample Number	Date	Preform Type	Master Type	Coating	Resin	Hardener/PHR	Parting Method	Curing Cycle, temp/hrs	Replica Surface Quality	Deviation	Remarks
17	7/8	4340 steel	A	Al	828	DEAPA/9	Force	104/15 + 126/2	Fair	< 4"	Some surface irregularities
18	7/9	416 steel	A	SiO + Au	828	DEAPA/9	Force	110/15 + 175/2	Fair	< 4"	Some surface irregularities
19	7/13	Mg	A	SiO + Au	826	DEAPA/9	Force	110/15 + 175/2	Poor	< 4"	Full of bubbles
20	7/14	4340 steel	A	SiO + Au	828	DEAPA/9	Force	110/15 + 125/2	Good	< 4"	Few bubbles
21	7/15	Ti	A	SiO + Au	828	DEAPA/9	Force	110/15 + 175/2	Good	< 4"	SiO transfers well
22	7/15	-130 steel	A	SiO + Au	828	DEAPA/9	Force	110/15 + 175/2	Good	< 4"	Some cleaning marks on replica
23	7/17	Al	A	SiO + Au	828	DEAPA/9	Force	110/63 + 175/1	Poor	< 4"	Surface full of bubbles
24	7/20	Al	A	Au	826	DEAPA/9	Force	125/2	Poor	< 4"	Surface full of bubbles
25	7/21	Al	A	SiO + Au	828	DEU PA/9	Force	110/15 + 175/15	Poor	< 4"	Surface full of bubbles
26	7/21	Al	A	SiO + Au	828	DEAPA/9	Force	110/15 + 175/2	Fair	< 4"	Many surface bubbles
27	7/23	Al	A	SiO + Au	828	DEAPA/10	Force	110/15 + 175/2	Fair	< 4"	Many small bubbles
28	7/24	Al	A	SiO + Au	828	DEAPA/10	Force	110/63	Fair	< 4"	Many surface bubbles
29	7/27	Al	A	SiO + Au	828	DEAPA/10	Force	110/16 + 175/3	Poor	< 4"	Surface full ... bubbles
30	7/28	Al	A	SiO + Au	828	DEAPA/10	Force	110/15 + 175/1	Fair	< 4"	Numerous surface bubbles
31	7/29	Al	A	Au	828	DEAPA/10	Force	110/15 + 175/7	Good	< 4"	Surface free of bubbles
32	8/10	Al	A	Au	828	DEAPA/10	Force	1.0/15 + 175/1	Good	< 4"	Few surface bubbles
33	8/11	Al	A	Au	828	DEAPA/10	Force	110/15 + 175/1.5	Good	< 4"	Flow marks near center
34	8/12	Al	A	?	828	DEAPA/10	Force	110/15 + 175/1	Good	< 4"	No bubbles

TABLE 9-II (cont.)
SPHERICAL MIRROR REPLICATION SUMMARY

Sample Number	Date	Preform Type	Master Type	Coating	Resin	Hardener/PER	Parting Method	Curing Cycle, temp/hrs	Replica Surface Quality	Deviation	Remarks
35	8/13	Al	A	Au	828	DEAPA/10	Force	115/15 + 175/1	Good	< 4"	No bubbles
36	8/14	Al	A	Al	828	DEAPA/10	Force	115/64 + 175/1	Good	< 4"	Surface recoated causing orange peel
37	8/19	Al	A	Al	828	DEAPA/10	Force	110/15 + 175/1	Fair	< 4"	Difficult to part causing plastic to crack
38	8/20	Mg	A	Cu	828	DEAPA/10	Force	125/15 + 175/1.5	Excellent	< 4"	Surface practically blemish free
39	8/25	Mg	A	Cu	828	DEAPA/10	Force	125/15 + 175/1.5 + 175/1	Excellent	< 4"	Surface blemish free

NOTES:

1. Sample number sequence ties in with the beginning of the current program.

2. All dates are in 1964.

3. Preform Al refers to aluminum, Mg to magnesium, Ti to titanium (see text for alloys).

4. Master: A is the first convex 8.4 inch radius of curvature master. Kanigen refers to 14.185 inch Kanigen coated steel, glass refers to a BSC-2 14.185 radius master from another program.

5. Coating: Ag = vacuum deposited silver, Al = vacuum deposited aluminum, Au = vacuum deposited gold, SiO + Au refers to silicon monoxide over gold, Cu = copper.

6. Adhesive resin 828 refers to Shell EPON 828 resin.

7. DEAPA refers to diethyl aminopropylamine; (PER) refers to the parts by weight of hardening agent added per 100 parts of resin.

8. Alignment refers to the method of layup.

9. Curing Cycle: Temperature of cure/the total hours of cure.

10. Parting Method: Force refers to parting with a fixture.

11. Reflector surface quality. Excellent refers to very good surface quality; good refers to acceptable surface quality; fair refers to minor surface defects; poor refers to gross surface defects.

12. Overall Deviation refers to the surface deviation in seconds.

13. Samples 12 through 22 were aligned with a fixture.

from bubbles caused by alignment, preform surface preparation, and adhesive properties.

With new tooling and unground preforms, the last five replicas were void free.

Another major problem besides bubbles, was the formation of a circular scum or flow lines on the plastic surface during layup. This is caused by an interruption in the layup process occurring before the master and the preform have fully joined. The new arbor press alignment fixture eliminated this problem. Fig. 9-2 shows a Ronchigram of a typical spherical replica.

9.2.2 General Optical Quality

Preform errors were calculated by three different methods:

1. Comparing the master and replica interferometrically
2. Comparing center and rim radii of curvature with a projection microscope and optical bench
3. Calculating from Ronchigram data

These calculations were made on a spot check basis. Interferometric tests indicate that some replicas approach and equal $\frac{1}{4}$ wave accuracy. Radii of curvature calculations showed that the replicas deviate by less than 4 seconds of surface error. Ronchigram calculations give a maximum surface error for a typical replica as 10 secs of arc. However, at least half of this error is due to the test apparatus.

Optical tests are described in Section 10. This spherical accuracy is about an order of magnitude greater than that needed for the paraboloid in the system requiring the high 20,000 g shock resistance.

9.2.3 Replicas from Submasters

Table 9-III summarizes the results of replicas made from plastic submasters. The Ronchigrams shown in Figs. 9-3 and 9-4 indicate that little accuracy has been sacrificed in the double

FIG. 9-2 TYPICAL RONCHIGRAM OF 4 INCH APERTURE
8.4 INCH RADIUS OF CURVATURE SPHERICAL
REPLICA VIEWED WITH A 175 LINES/INCH
GRATING SCREEN

TABLE 9-III
REPLICA SUMMARY FROM SUBMASTERS

Sample Number	Date	Preform Type	Submaster Number	Coating	Resin	Hardener/PHR	Curing Cycle temp/hrs	Replica Surface Quality	Remarks
1	7/23	Al	1	Cu/SiO/Au	828	DEAPA/10	1.0/15 + 175/2	Fair	Surface full of bubbles
2	7/22	Al	2	SiO/Au	828	DEAPA/10	1.0/63	Good	Difficult to part. Few bubbles
3	9/14	Al	7	Ag/Cr	828	DEAPA/10	110/15 + 175/1	Very good	Sleeks in Submaster Replicated

NOTES:

1. Sample number sequence starts with the beginning of the current program.
2. All dates are in 1964.
3. Al refers to an alumina preform.
4. Submaster log number refers to the number assigned to each submaster.
5. Coating: Cu/SiO/Au refers to copper over silicon monoxide over gold. SiO/Au refers to silicon monoxide over gold. Ag/Cr refers to silver over chromium.
6. Resin: Number 828 refers to Shell EPON 828 resin.
7. DEAPA refers to diethyl aminopropylamine; (PHR) refers to the parts by weight of hardening agent added per 100 parts of resin.
8. Curing Cycle: Temperature of cure/the total hours of cure.
9. Replica surface quality: Good refers to acceptable surface quality; fair refers to minor surface defects; poor refers to gross surface defects.

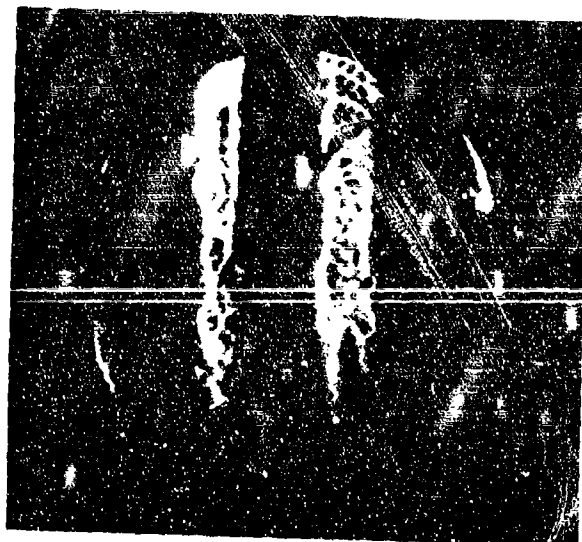FIG. 9-3 REPLICA FROM SUBMASTER NUMBER ONE
175 LINES/INCH RONCHI SCREEN

FIG. 9-4 REPLICA FROM SUBMASTER NUMBER TWO
175 LINES/INCH RONCHI SCREEN

replication process. The line in Fig. 9-3 is the replica of the master crack. The jagged line in Fig. 9-4 is caused by flow marks on the plastic during layup. The last replica made from a sub-master was far superior to the first two in surface quality and accuracy.

10. OPTICAL AND ENVIRONMENTAL TESTS

10.1 Optical Tests

The corner prism replicas were tested by the collimation tests described in the previous program. The spherical replicas were tested by Ronchi, interference, and radius of curvature measurements.

10.1.1 Ronchi Test

The Ronchi test apparatus is shown in Fig. 10-1. The schematic drawing of this apparatus with a camera box for taking Ronchigrams is shown in Fig. 10-2. The Ronchi test is extensively used as a simple method of determining sphericity, though it can be used with a known reference to roughly check production aspherical elements. Basically the Ronchi test requires a pinhole light source as small or smaller than the Ronchi grating screen separations projected from the same effective radius of curvature at which the screen is located. The projected "image" of the grating screen, as viewed by the eye or on photographic film, is a function of the geometry of the optic under test. A perfect sphere will produce perfectly straight lines. This test can be used to quantitatively calculate the surface errors of the replica element if the scaling factors, radius of curvature, and measured Ronchigram image deviation are known.

Ronchigrams were made of all replicas fabricated using a 175 lines per inch grating screen. The maximum surface error as calculated from the Ronchigrams is in the range of ten seconds. However, at least half of this error is due to inaccuracy in the beam splitter used in the Ronchi tester. Mirrors of this f/ratio must be tested with a light source that is on axis and has a wide field of view. This necessitates the use of a thin beam splitter for minimum distortion. A flat and parallel beam splitter of the thickness required is difficult to fabricate and mount.

SPHERICAL REPLICA MIRROR

PINHOLE LIGHT HOUSING

BEAM SPLITTER

RONCHI SCREEN

FIG. 10-1 RONCHI TEST APPARATUS

ZIRCONIUM ARC
PROJECTION OPTICS
PINHOLE
DICHROIC MIRROR
SPHERICAL MIRROR
CAMERA, WITHOUT LENS
PHOTOGRAPHIC FILM
RONCHI SCREEN
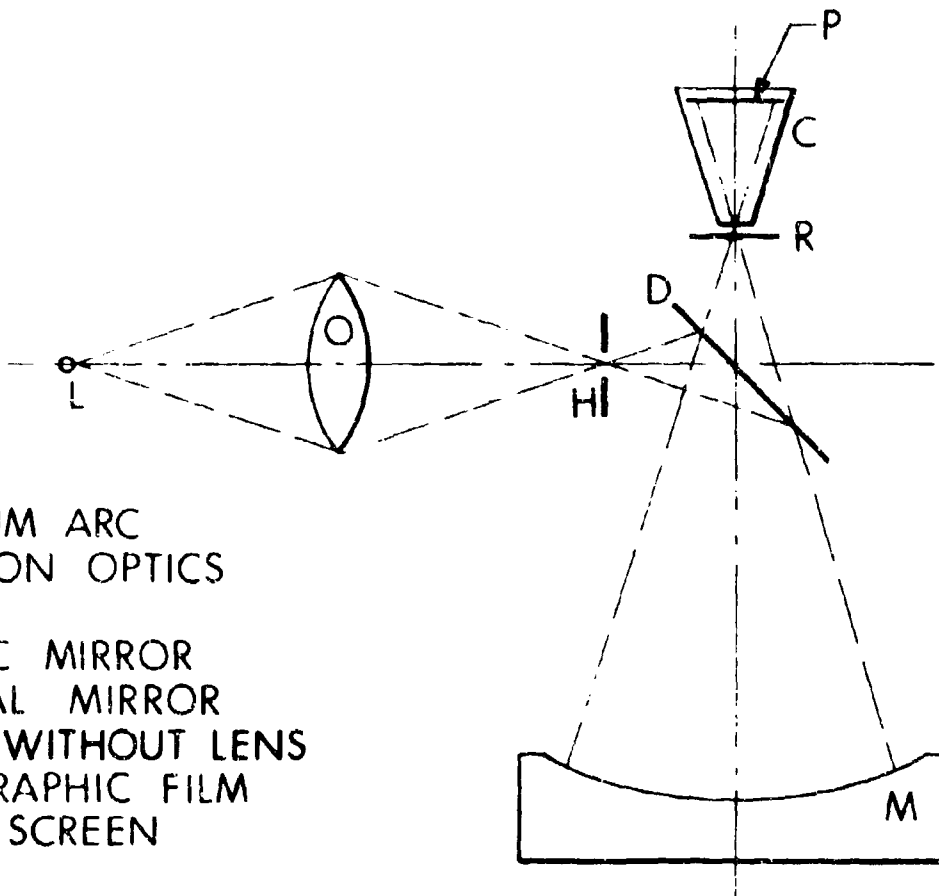
FIG. 10-2   RONCHIGRAM TEST SCHEMATIC

Allowing for the beam splitter, the Ronchigrams shown throughout this report indicate a high degree of development in the state of the art of precision replication.

10.1.2 Interference Test

The interference test involves the use of the glass master placed in near optical contact with the replica, plus a monochromatic mercury light source. The variation in Newton rings between the master and replica is an indication of the replica accuracy. Since this test tends to abrade the replica, most optical testing was done by taking Ronchigram pictures.

10.1.3 Radius of Curvature Test

Before the Ronchi tester was completed, the radius of curvature of the replicas was checked at two or more zones. The variation in curvature is a function of the spherical accuracy. The replicas checked ranged from a 0.010-inch variation in curvature when replication started to less than a 0.001-inch variation after the fourth replication.

Though fairly accurate, this test only measured the curvature at discrete points and was limited by the lens bench vernier scale.

10.2 Environmental Tests

A number of tests were conducted with flat, spherical and corner prism replicas of different surface coatings and fabrication date to evaluate their resistance to various environmental conditions. Most of the results obtained indicate satisfactory performance. Additional tests are needed to confirm and extend these data.

10.2.1 High-Low Temperature Cycling

Table 10-I lists the results of a test series wherein 12 flat plastic replicas from another program, with and without metallic vacuum coating, were exposed in a test chamber to 12 consecutive temperature cycles of between $-70^\circ F$ and $+165^\circ F$ for a period of 72 hours. The temperature rise and fall between the maxima and minima was kept

TABLE 10-I

HIGH-LOW TEMPERATURE CYCLING TEST

Sample Number	1	2	3	4	5	6	7	8	9	10	11	12
Fabrication Date	4-20	4-21	6-2	6-4	6-5	6-6	5-12	5-19	5-20	5-21	5-22	5-26
Aluminum Coating	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No
Flatness in λ at Fabrication Date	1/8	1/2	1/4	1/8	1/4	1/8	NR*	1/8	1/4	1/4	1/4	1/4
Flatness in λ Prior to Test	1/8	1/2	1/4	1/8	1/4	1/8	NR*	1/8	1/8	1/4	1/4	1/4
Flatness in λ After Test	1/4	1/4	1/4	1/4	1/8	1/8	3/8	1/8	1/8	1/8	1/2	1/8
Reflectance % at 31° Incidence Prior to Test	87.5	89.2	89.2	89.0	89.3	89.7	5.1	5.1	5.2	5.0	5.2	5.4
Reflectance % at 31° Incidence After Test	88.6	89.8	89.9	91.9	91.2	91.5	5.2	5.1	5.1	5.1	5.2	5.3

intentionally at the steepest possible gradient (1½ hours). The samples, thus, had approximately 1½ hours to reach equilibrium at maximum and minimum temperatures.

Similar tests were made with spherical and corner reflector replicas, vacuum coated with gold next to the plastic surface, followed by a SiO top coating.

The combined tests included, therefore, pyrex glass as well as aluminum die cast preforms.

None of these samples showed any evidence of optical or mechanical degradation contributable to the test conditions

Four spherical replica mirrors were tested for 24 hours to the storage temperature extremes of $+165^{\circ}$F to -45°F. The temperature was cycled once during 24 hours. Replicas selected for testing represented four different preform materials:

1. Aluminum
2. Magnesium
3. 4340 Steel
4. 416 Steel

The chamber dehumidifier did not work properly during these tests and resulted in ice formation at the low temperature region. This test did not produce any significant damage to the exposed replicas. Surface characteristics remained unchanged except for minor oxidation of the steel preforms. In all cases the optical characteristics remained unchanged.

The above four replicas were tested for an additional 24 hours at the storage temperature extremes of $+170$ to -75°F. The results of this test were identical to those of the previous test; surface and optical characteristics remained unaltered. Additional oxidation was observed on the steel preforms. Figures 10-3 through 10-19 summarize the temperature cycling and shock tests.

10.2.2 Shelf Life

A systematic shelf life study has not been consistently carried on throughout the entire span of this work; however, spot checks

FIG. 10-3 REPLICA 4, BEFORE SHOCK TEST

FIG. 10-4 REPLICA 10, BEFORE SHOCK TEST

FIG. 10-5 REPLICA 10, AFTER SHOCK TEST

FIG. 10-6   REPLICA 10, AFTER FIRST
             ENVIRONMENTAL TEST
             -45 to +170°F

FIG. 10-7   REPLICA 10, AFTER SECOND
             ENVIRONMENTAL TEST
             -80 to +170°F

FIG. 10-8   REPLICA 14, BEFORE SHOCK TEST

FIG. 10-9   REPLICA 14, AFTER SHOCK TEST

FIG. 10-10   REPLICA 14, AFTER FIRST
ENVIRONMENTAL TEST
-45 to +170°F

FIG. 10-11   REPLICA 14, AFTER SECOND
ENVIRONMENTAL TEST
-80 to +170°F

FIG. 10-12   REPLICA 17, BEFORE SHOCK TEST

FIG. 10-13   REPLICA 17, AFTER SHOCK TEST

FIG. 10-14   REPLICA 17, AFTER FIRST
ENVIRONMENTAL TEST
-45 to +170°F
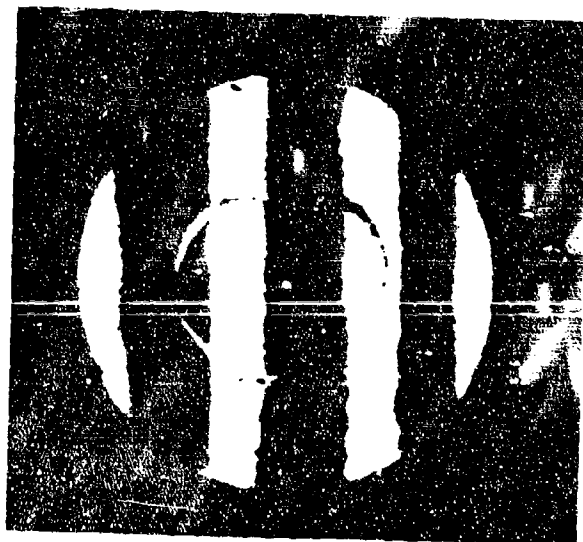
FIG. 10-15   REPLICA 17, AFTER SECOND
ENVIRONMENTAL TEST
-80 to +170°F

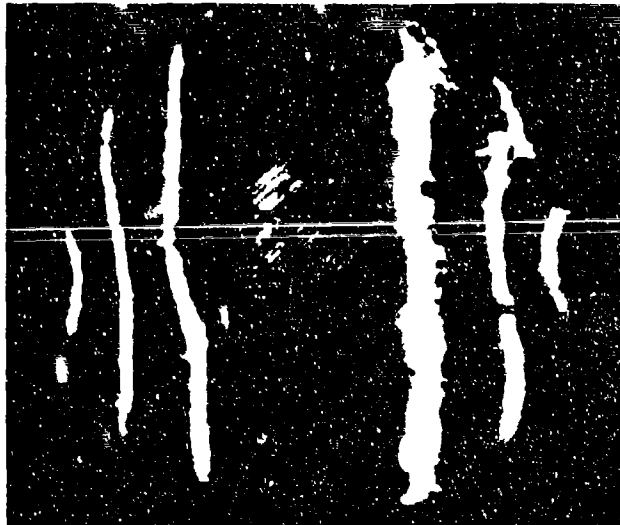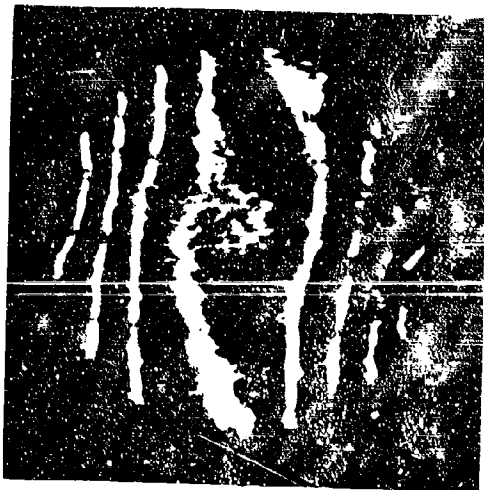FIG. 10-16 REPLICA 18, BEFORE SHOCK TEST
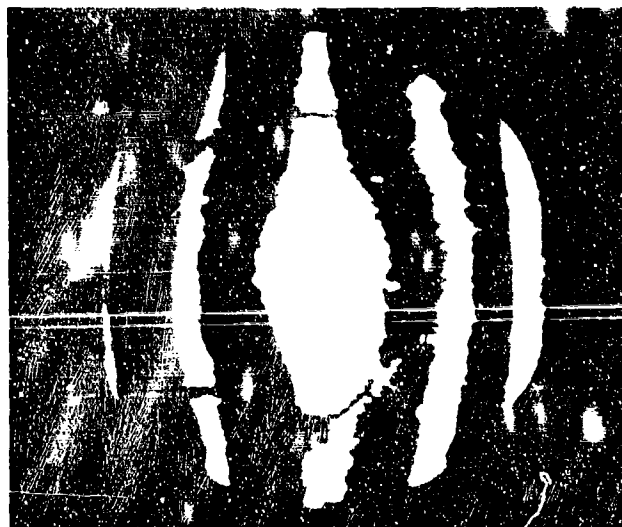
FIG. 10-17 REPLICA 18, AFTER SHOCK TEST
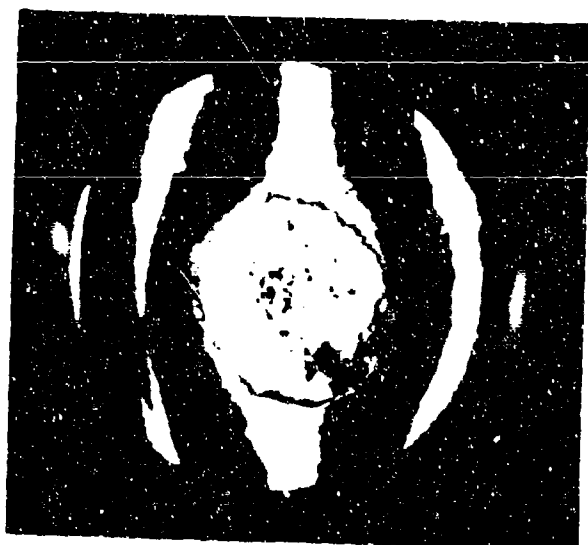
FIG. 10-18   REPLICA 18, AFTER FIRST
ENVIRONMENTAL TEST
-45 to +170°F
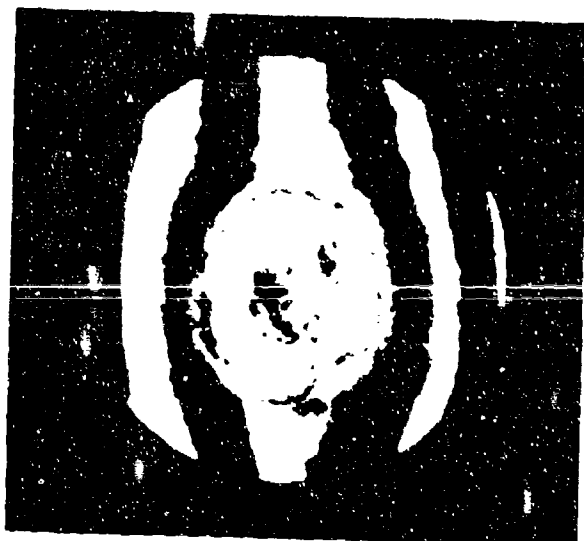
FIG. 10-19   REPLICA 18, AFTER SECOND
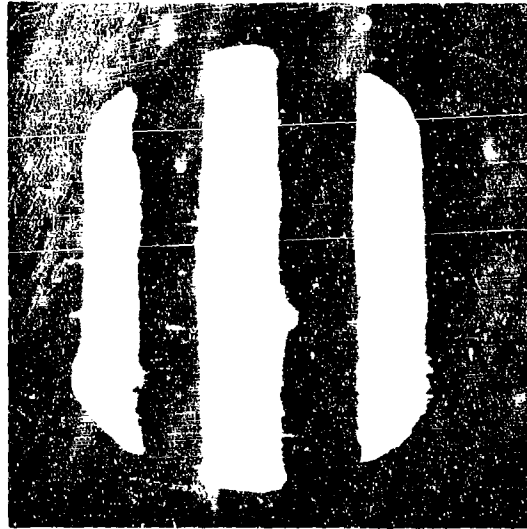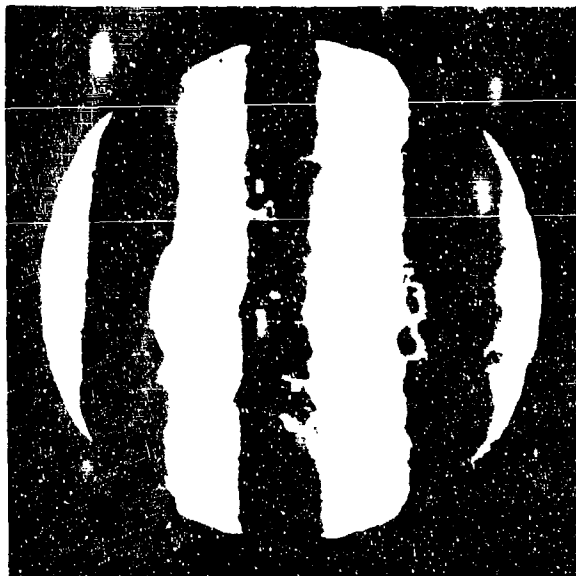ENVIRONMENTAL TEST
-80 to +170°F

showed no evidence of degradation. To the contrary, optical quality in some replicas had improved. The most plausible explanation of this observance is that gradual stress relief occurred with a corresponding improvement in optical accuracy.

In another program quantitative optical flatness was conducted daily on flat replicas over a 1 week period to observe consistency of readings. The results are listed in Table 10-II. It is quite evident that the flatness readings improved considerably with time on the replicas that showed inferior readings on date of fabrication.

10.2.3 Humidity

Considerable difficulties were encountered when testing plastic replicas with plain aluminum mirror coatings at high relative humidity. Partial or total loss of specular reflectance resulted when the test samples were stored for even less than 12 hours in an atmosphere of 100 percent relative humidity at a temperature of $135^\circ F$.

The test arrangement consisted of a desiccator in which the samples were arranged face down. The bottom of the desiccator was filled with distilled water to 1 inch height. The desiccator with the samples was placed in an oven.

The cause of this adverse effect was found to be water vapor and bulk penetrating the interface between resin and metallic layer which in these tests consisted solely of vacuum coated aluminum. This resulted in lifting and destruction of the mirror finish, as shown in Fig. 10-20.

Further studies led to a complete elimination of these difficulties through the use of adhesion promoters and protective coatings. This permitted exposure of plastic replica mirrors to a moisture saturated atmosphere at $135^\circ F$ for 72 hours without any visual change in reflectance or degradation of ether optical or mechanical properties.

This test included evaluation of SiO and of chromium (vacuum coatings) as moisture barriers and adhesion promoting coatings

TABLE 10-II

OPTICAL FLATNESS READINGS ON FLAT REPLICA SAMPLES STORED FOR 1 WEEK

Preform #	31	60	25	23	76	28	98	42
Fabrication Date	7-27	7-27	7-28	7-28	7-28	7-28	7-27	7-27
Flatness) in λ Readings)								
7.-27	1/4	1/4	N.R*	N.R*	N.R*	N.R*	1/2	1/2
" " 7.-28	1/4	1/4-1/2	1	1/4-1/2	1	1/8	1/4-1/8	1/2
" " " 7.-29	1/8	1/8	1/4-1/2	1/4-1/2	1/2-1	1/8	1/4	1/4-1/2
" " " " 7.-30	1/4-1/8	1/8	1/4	1/2	1/2	1/8	1/4-1/8	1/4
" " " " " 8.-3	1/4	1/4-1/8	1/4	1/4-1/2	1/2	1/8	1/4-1/8	1/4-1/8

*N.R = No reading possible.
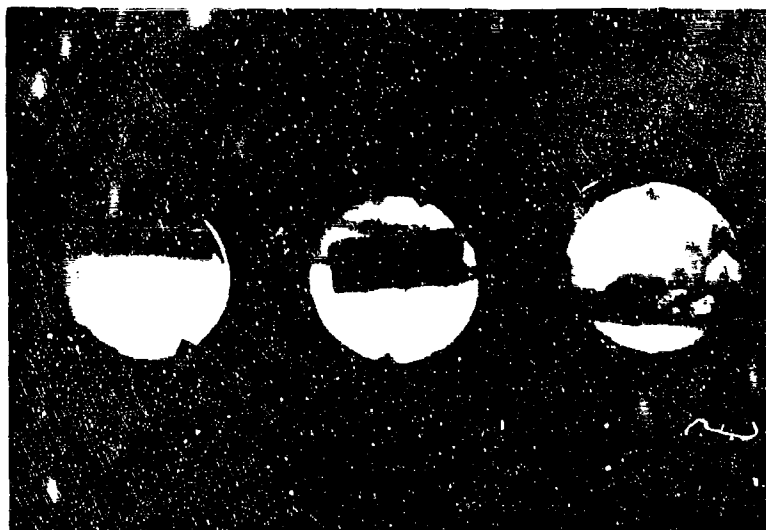
FIG. 10-20 HUMIDITY TEST ON FLAT PLASTIC
            REPLICA MIRRORS

between the replica plastic surface and an aluminum vacuum coating. In addition, SiO was also evaluated as a protective top coating for the aluminum mirror coating. The results of this, consisting of 3 samples, are shown in Table 10-III. The orange peel observed in Sample 3 may possibly be caused by the relatively large difference in thermal expansion coefficient between chromium, aluminum, and epoxy resin. Expressed in units of in/in ^{o}F x 10^{-6}, these coefficients are:

Chromium	4.0
Epoxy resin, unfilled	25-36
Aluminum	13-15

Additional samples made since the program ended have been free from the orange peel associated with the third sample. An explanation for this is presently not available.

10.2.4 Salt Fog

The salt fog test was conducted to determine the resistance of materials and fabricates (replicas) to the effects of a salt atmosphere. To accelerate this test, the samples are exposed to moisture and salt concentrations considerably greater than encountered in normal service.

10.2.4.1 Operating Conditions

The test is performed at a temperature of 95 (+2, -3)^{o}F. A 5 ($\pm$ 1)% sodium chloride solution is atomized into the test chamber under the following conditions:

1. Nozzle pressure between 12-18 ps'.

2. Atomizer orifice between 0.02-0.03 inch in diameter.

3. Atomizer delivery rate is regulated so that a collecting receptacle, placed at any point in the test chamber will collect from 0.5 - 3.0 cc of solution for each 80 square centimeters of horizontal collecting area.

4. Collected salt solution shall have a specific gravity of from 1.023 to 1.037 and a pH range of 6.5 - 7.2.

TABLE 10-III

SUMMARY OF CORNER PRISM REPLICAS

Sample #	1	2	3
Preform # (Pyrex)	9	63	7
Coating Sequence beginning with coating next to plastic surface	SiO Aℓ	SiO Aℓ SiO	Chromium SiO Aℓ SiO
Results by Visual Inspection	Orange peel, otherwise excellent	Orange peel, otherwise excellent	Orange peel, otherwise very good
Adhesive Peel Test	Completely removed	Completely removed	Excellent
Conclusions	Sample shows that SiO as a primer coat between the resin surface and the mirror coating contributes successfully to the preservation of the original reflectance of the aluminum layer. However, the bond between SiO and the resin is practically destroyed as the result of the test conditions.	Similar to No. 1.	Test indicates that chromium is a very successful adhesion promoter.

5. Compressed air entering the chamber shall be at a temperature of at least 35°F and have a relative humidity of at least 85 percent.

6. The chamber must be properly vented to prevent pressure buildup and allow uniform distribution of the salt fog.

10.2.4.2 Apparatus

A small salt fog chamber with necessary accessories was devised and assembled, using available laboratory glassware and other items (Fig. 10-21). A schematic illustration of this test equipment is shown in Fig. 10-22. The letters used refer to the following parts:

A   1 - 12 x 12" bell jar

B   2 - 4 liter pyrex filter flasks

C   1 - Pyrex atomizer

D   2 - thermometers (mercury)

E   2 - thermostatically controlled hot plates

F   1 - pressure regulator

G   2 - # 11.5 rubber stoppers

H   1 - airstone

I   1 - drying tube

J   glass wool

K   1 - 1 -14" diameter perforated masonite sheet (1/8" thick)

L   1 - adjustable pinet clamp

M   1 - glass "T"

O   1 - pressure indicator

P   insulation material

R   drain

S   1 - sink

T   test samples

U   sample support

V   salt solution

W   distilled water

FIG. 10-21   SALT SPRAY APPARATUS

(SEE TEXT FOR NOMENCLATURE)
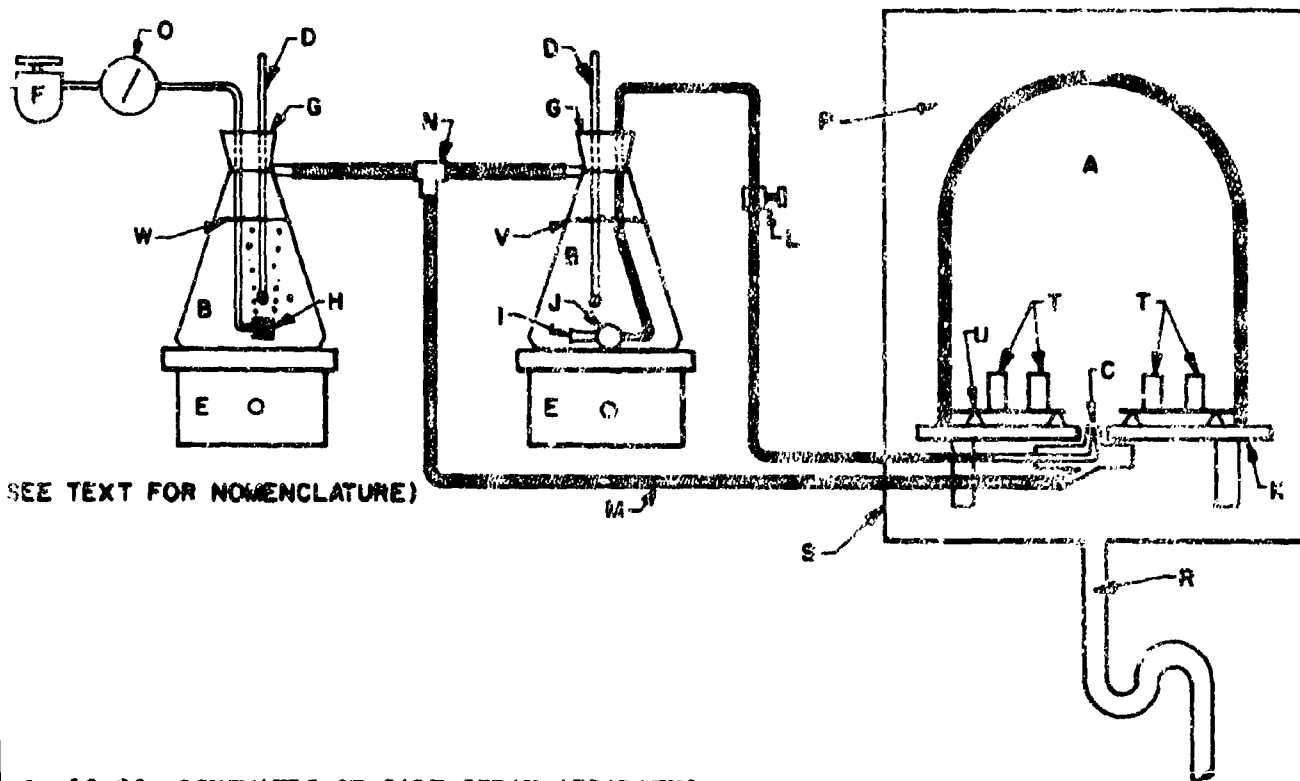
G, 10-22 SCHEMATIC OF SALT SPRAY APPARATUS

10.2.4.3 Operation

The hot plates are turned on and adjusted to maintain the salt solution and the water at a temperature of $160^{\circ}F$. The compressed air is turned on and the pressure adjusted to 12 psi. Air leaving the bubble chamber was measured at $105^{\circ}F$ with a relative humidity of 86 percent. Heat loss in the plastic tubing is approximately $10^{\circ}F$. Therefore, the air entering the chamber meets the operational requirements of 95 (+2, -3)$^{\circ}F$. Constant temperature within the bell jar was maintained by insulating it with styrofoam and asbestos cloth. Trial chamber operation was carried out for 24 hours prior to the test run to adjust the delivery rate of the salt solution and the chamber operational temperature.

Table 10-IV summarizes the resistance of 6 different reflective replica samples to 48 hours salt fog exposure.

10.2.4.4 Discussion of Results

1. Glass preforms were unaffected by the salt fog.

2. Aluminum and steel preforms were severely corroded by the salt fog.

3. Unprotected aluminum surfaces were completely destroyed by exposure to salt fog.

4. Gold reflective surfaces, with and without SiO protective top coating were corrosion-resistant. However, optical and cosmetic quality was degraded due to blistering and blooming effects caused by preform corrosion; assumedly through pinholes in the gold.

5. The chromium-primed samples of reflective aluminum coatings withstood exposure to salt fog well except for some edge and pinhole attack.

6. Only the chromium-primed samples passed a pressure sensitive, tape-peel test.

7. Metal preforms, sensitive to corrosion, have to be protected.

8. Research on salt spray resistance since the program ended has improved the adhesion and corrosion resistance of gold-coated replicas.

TABLE 10-IV

SALT FOG TEST

Replica Test Samples	Preform Number	Preform Material	Coatings	Effects of Salt Fog		
				Preform	Reflective Surface	Peel Test
1 Flat	91	Pyrex	Aluminum	None	Completely destroyed	---
2 Flat	15	Pyrex	Aluminum Chromium SiO	None	Completely destroyed epoxy film peeled off	---
3 Flat	7	Pyrex	SiO Aluminum SiO	None	None except slight edge blooming	Excellent bond
4 Hollow corner reflector	-	Aluminum	Gold	Heavy corrosion	Corroded preform through pinholes; edge blister	Unsatisfactory
5 8.4" concave sphere	-	4340 Steel	Gold	Extremely heavy corrosion	Edge corrosion from preform, also condensation streaks, blisters	Unsatisfactory
6 8.4" concave sphere	-	Aluminum	Gold SiO	Heavy corrosion	Edge corrosion and corroded preform through pinholes, blisters	Unsatisfactory

10.2.5 Preform Shock Resistance

A conservative analysis of the preform shock resistance, based on the minimum thickness of the preform shown in alternate A, Fig. 5-2, is given in Appendix C. The analysis indicates that all the materials chosen should withstand the shock environment if the assumptions made are correct. In addition, since the preforms are tapered rather than of constant thickness, the edge stress may be as much as 1/4 to 1/5 the values calculated in the analysis. Forthcoming experimental shock tube tests should determine the validity of the analysis.

Replicas 4, 10, 14, 17, and 18 were tested at Frankford Arsenal at shock levels of 20,130, 20,190, 20,400, 19,070, and 18,560g respectively. These replicas are shown in Figs. 10-3, -4, -8, -12, -16 before shock testing and Figs. 10-5, -9, -13, and -17 after shock testing. Replica No. 4 was left at Frankford Arsenal for further shock and environmental testing. There was no visual failure of the plastic surfaces after shock tests. However, on two of the four replicas tested at EOS some preform distortion resulted.

On replica No. 10 the visual distortion was in the form of orange peel aligned in the same direction as the aluminum preform inclusions. The Ronchigram in Fig. 10-5 indicates the orange peel and the general degree of preform distortion. The preform distortion is probably due to several causes:

1. Thin preform section at the replica center.
2. The nonuniform lightening holes in the rear of the preform; alternate A design.
3. The alloy used probably did not have maximum yield strength.

Replica No. 14 survived the shock test with no degradation in the optical accuracy or plastic surface. This replica had a magnesium preform which was about 5/8 inch thick at the center and had no rear lightening holes; alternate C design. Its greater resistance to the shock environment can be attributed to:

1. Thickness
2. Lack of irregularity

3. High dampening of magnesium

Replica No. 17 was made with the same preform con-
figuration as replica No. 14 but of 4340 steel. It showed no distor-
tion either.

Replica No. 18 was made of 416 stainless steel and
had only the concave lightening of the preform back; alternate D de-
sign. This replica also distorted slightly to a regular elliptical
shape.

Several conclusions can be tentatively drawn from
this small shock test sample:

1. The replica plastic surfaces will easily survive the 20,000g
   shock level of the Frankford Arsenal shock test.

2. For the same weight magnesium preforms may offer greater
   shock resistance than aluminum.

3. The distortion even when present is small.

APPENDIX A

THEORETICAL ANALYSIS

A theoretical analysis of the replica system has been made to determine tolerable ranges of important variables and to provide a foundation and guide for the experimental program. This section summarizes the analyses and derivations. The basis of the analysis is the interaction between the adhesive layer and the preform. Among the topics which have been considered are:

1. The allowable variation in adhesive layer thickness as a function of adhesive shrinkage characteristics (this places a requirement on preform surface accuracy).

2. Effect of adhesive shrinkage on bending.

A.1 Variables, Assumptions, and Nomenclature

Among the variables involved in the analysis are:

Plastic Adhesive

Modulus of elasticity

Cure shrinkage

Thermal expansion coefficient

Cure temperature

Adhesive value

Thickness

Heat transfer coefficient

Homogeneity

Poisson's ratio

Backing Structures or Preforms

Modulus of elasticity

Thermal expansion coefficient

Thickness

Surface finish

Dimensional tolerances

Shape

Homogeneity

Heat transfer coefficient

Poisson's ratio

For analysis purposes, the following assumptions were made:

1. Adhesive and backing structure are each homogeneous with uniform physical characteristics

2. Temperature is uniform throughout structure

3. Adhesive strength is sufficient to transfer all stresses without failure.

The following nomenclature was used in the analysis and derivation:

s	Stress (lb/in^2)
ε	Strain (in/in)
E	Modulus of elasticity (lb/in^2)
Y	Deflection (in)
t	Thickness (in)
L	Length (in)
$(\ )_p$	Denotes preform
$(\ )_r$	Denotes adhesive layer
$(\ )_c$	Denotes curing effects
$(\ )_t$	Denotes thermal effects
k_t	Coefficient of thermal expansion (in/in (^{o}F)
T	Ambient temperature (^{o}F)
T_o	Datum temperature (^{o}F)
υ	Poisson's ratio
$(\ )_x$	Denotes x axis
$(\ )_y$	Denotes y axis
$(\ )_z$	Denotes z axis

T_c Resin cure temperature ($^\circ$F)

R   Radius of curvature (in.)

r_p Radius of preform disc (in)

A.2   Effects of Resin Shrinkage Acting Normal to Plane of Replica Surface

Consider the ideal case of an adhesive-preform laminate with unit length and width. The thickness is $(t_r + t_p)$.
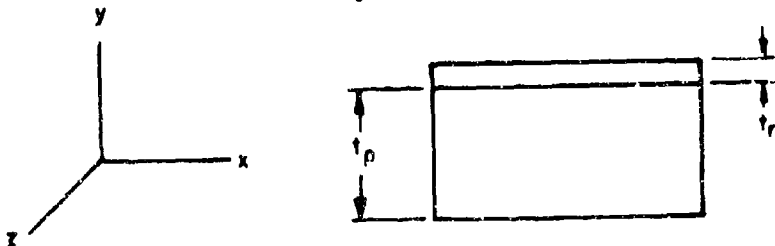
the adhesive thickness is negligible compared with the preform thickness. The object is to determine the maximum allowable variation in adhesive thickness, t_r, which will still give adequate surface accuracy (e.g., $/4 \lambda$) in spite of curing strain, δ_{cr}, and temperature strain, δ_{tr}. Other assumptions are:

1. Strains perpendicular to the plane of the reflecting surface are due only to curing and temperature strains.

2. Bending of the backing structure does not relieve adhesive skin stresses.

3. Backing structure is rigid, perpendicular to replica face.

4. Physical properties of adhesive and preform are uniform throughout.

5. Assume typical adhesive physical properties on the basis of Epon$^{(R)}$ 828 adhesive using Z curing

agent, 20 phr unfilled, with cures of 2 hr at 175°F and 2 hr at 300°F.

6. Resin layer is cured at 70°F (this value is used for example calculation purposes only. Actually, this temperature range would be too low to cure Epon 828 with the Z curing agent.)

7. Operating temperature range is -40°F to +125°F.

The details of the analysis are given below.

A.2.1 Analysis of Adhesive Shrinkage Normal to Replica Surface

The case to be analyzed is that of an adhesive-preform laminate of unit length and width and of thickness $(t_r + t_p)$. It is assumed that $t_r \ll t_p$. The object is to determine maximum allowable adhesive thickness variation which will still give adequate surface accuracy (e.g., $1/4 \lambda$). Strains induced by cure shrinkage and temperature change will be considered.

Resin properties are assumed to be uniform throughout. The properties of Epon 828 cured with "Z" are assumed to be typical for rigid epoxy adhesives. The linear coefficient of thermal expansion for Epon 828 is approximately

$$k_{tr} = k_{trx} = k_{try} = k_{trz} = 2.83 \times 10^{-5} \text{ in/in } °F$$

The linear shrinkage for Epon 828 due to curing is assumed to be

$$\delta_{cr} = \delta_{crx} = \delta_{cry} = \delta_{crz} = -4 \times 10^{-3} \text{ in/in}$$

The minus sign is used for mathematical convenience. Poisson's ratio for Epon 828 is assumed to be

$$\upsilon = 0.25$$

Because the properties of the preform are assumed to be uniform throughout, the linear coefficients of thermal expansion are

$$k_{tp} = k_{tpx} = k_{tpy} = k_{rpz}$$

r this analysis, the maximum permissible surface deviation will be
sumed to be one quarter wavelength of mercury light, where

$$1/4 \; \lambda \; = \; 5.37 \times 10^{-6} \; \text{in.}$$

.e total normal shrinkage, δ_y, is a function of the adhesive cure
rinkage, δ_{cr}; ambient temperature, T; cure temperature, T_c; linear
.fficients of thermal expansion, k_{tp} and k_{tr}; and Poisson's ratio
r the adhesive, υ_r. Then

$$= \; \delta_{cr} \; + \; f \; (k_{tr}, \; k_{tp}, \; \upsilon_r, \; T) \; + \; f \; (k_{tr}, \; \upsilon_r, \; T_c) \qquad . \qquad (1)$$

$$= \; \delta_{cry} \; - \; \upsilon_r \; (\delta_{crx} \; + \; \delta_{crz}) \; + \; (T - T_o) \; \left[k_{try} \; - \; \upsilon_r (k_{tpx} \; - \; k_{trx}) \; - \; \upsilon_r \; (k_{tpz} - k_{trz}) \right.$$

$$+ \; (T_c - T_o) \; \left[k_{try} \; - \; \upsilon_r \; (k_{tpx} \; - \; k_{trx}) \; - \; \upsilon_r \; (k_{tpz} \; - \; k_{trz}) \right]$$

r practical purpose $k_{tp} \leq k_{tr}$, and as a first approximation, $k_{tp} = 0$.
erefore, with the elimination of k_{tp} and the cancellation of the T_o
rm, the above equation for δ_y reduces to:

$$\delta_y \; = \; \delta_{cry} \; (1 + 2 \; \upsilon_r) \; + \; (T - T_c) \; \left[k_{try} \; (1 + 2 \; \upsilon_r) \right] \qquad (2)$$

tially we can assume a room temperature cure,

$$T_c \; = \; T_o \; = \; 70^{\circ}\text{F}.$$

lthough Epon 828-Z does not cure at 70°F, adhesives with similar
vsical properties are available which will cure at this temperature.)
.m the above equation the absolute value of δ_y, $\left| \delta_y \right|$, is a maximum
T $= -40^{\circ}\text{F}$, the bottom of the operating range. The absolute value of
. shrinkage times the maximum variation in resin thickness gives the
imum surface variation of a surface which was optically perfect
.ore curing. It has been assumed that the maximum surface deviation,
must be equal to or less than $1/4 \; \lambda$. Then

$$\left| \delta_y \right| \; \left[(t_r)_{max} \; - \; (t_r)_{min} \right] \leq 1/4 \; \lambda \qquad (3)$$

$$(t_r)_{max} \; - \; (t_r)_{min} \; = \; t_r \qquad (4)$$

Therefore

$$|\mathcal{E}_y| \, \Delta t_r \cdot 1/4 \, \lambda \tag{5}$$

or

$$\Delta t_r = \frac{1/4 \, \lambda}{|\mathcal{E}_y|} \tag{6}$$

Substituting for $1/4 \, \lambda$ and $|\mathcal{E}_y|$

$$\Delta t_r = \frac{5.37 \times 10^{-6}}{|-4 \times 10^{-3} \times 1.5 - 110 \times 2.83 \times 10^{-5} \times 1.5|}$$

$$\approx 0.5 \times 10^{-3} \text{ in.}$$

Then the maximum <u>variation</u> in adhesive layer thickness must be 5×10^{-4} inches or less to achieve reflective surface accuracy within 1/4 wavelength after adhesive shrinkage and at the minimum operation temperature. This case is for a preform with zero thermal expansion coefficient. However, since most metals, glasses, and ceramics have low expansion coefficients compared with plastics, this assumption is reasonable although somewhat conservative. By reducing shrinkage and by more closely matching the linear thermal expansion coefficients of the adhesive and the preform this tolerance can be increased. This tolerance dictates preform surface smoothness and accuracy. Tolerances of this order are achievable by conventional manufacturing methods.

For other cure temperatures, the maximum adhesive layer thickness variation is given by (after numerical reduction):

$$\Delta t_r = \frac{0.126}{141 + (T_c - T)} \text{ inches, where } T_c \text{ and } T \text{ are in } {}^\circ F \tag{7}$$

This is plotted in Figure A-1. This suggests that a room temperature cure should precede any high temperature curing in order to accomplish the initial setting of the resin at a low temperature. However, there may be other reasons for not curing initially at room temperature.
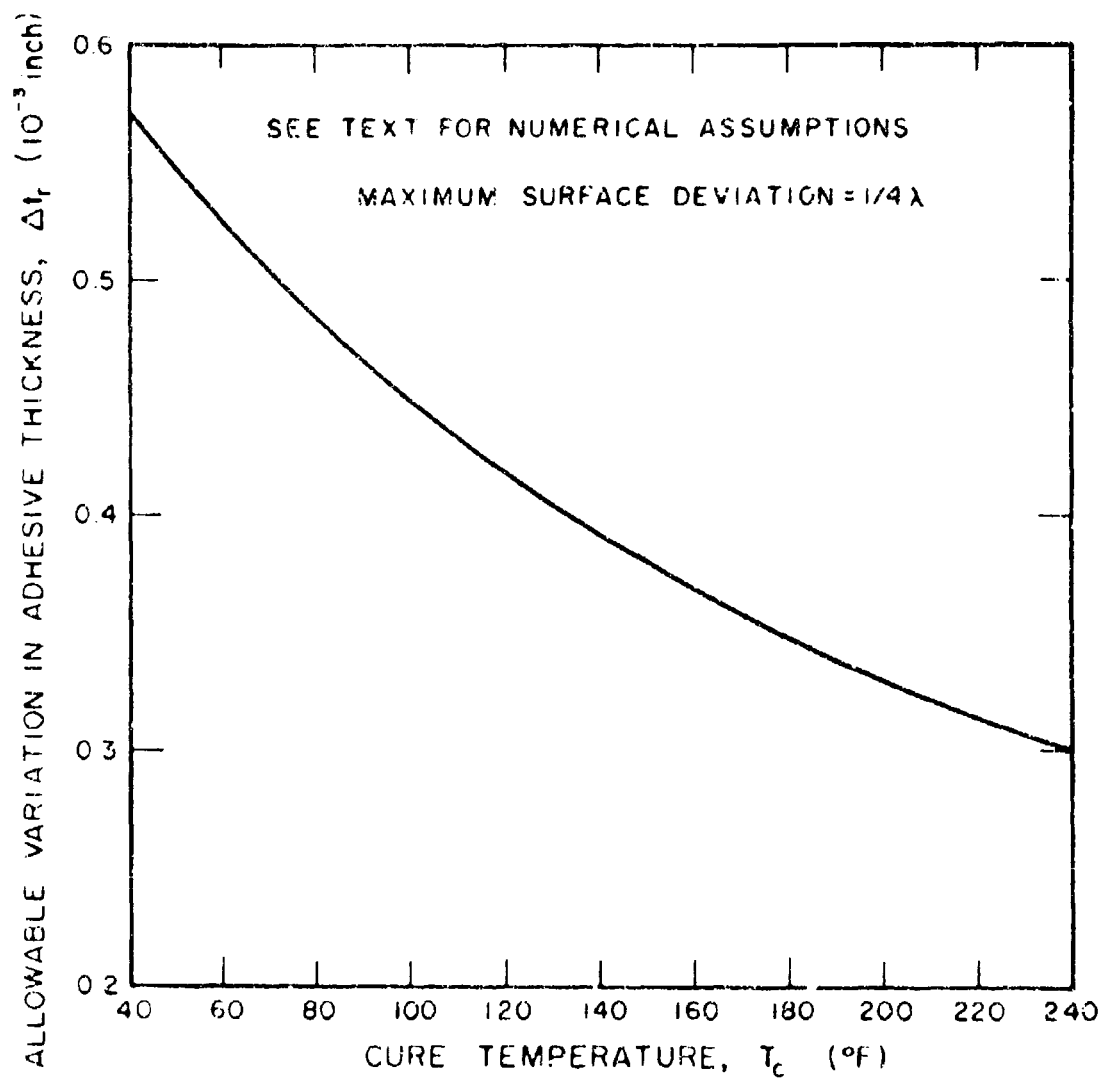
FIG. A-1 ALLOWABLE ADHESIVE SURFACE THICKNESS VARIATION VS
CURE TEMPERATURE

The above analysis applies to both flat and spherical replicas and preforms. However, aspheric replicas are of greater potential interest. Consider the fabrication of a concave paraboloidal.

For lowest preform costs, it is desirable to fabricate paraboloidal replicas using spherical preforms with a radius of curvature equivalent to that of the vertex sphere of the paraboloid, or $R = 2f$ where R is the spherical radius of curvature and f the paraboloid focal length. The difference between the sphere $y = R\sqrt{1 - \frac{x^2}{R^2}}$ and the parabola $y = \frac{x^2}{4f}$, dy is then given by

$$dy = R - R\sqrt{1 - \frac{x^2}{R^2}} - \frac{x^2}{4f} \qquad (8)$$

by expanding $(1 - \frac{x^2}{R^2})^{1/2}$ in a series this then reduces approximately to

$$dy = \frac{x^4}{64f^3} \qquad (9)$$

since $f/no = \frac{f}{2x}$, dy is also given by

$$dy = \frac{x}{512 \ (f/no)^3} \qquad (10)$$

A plot of dy versus replica diameter, D, where $D = 2x$ is given in Figure A-2 for parabolas of various f/numbers. Using the 5×10^{-4} inch plastic thickness variation criteria developed above this figure indicates that a 4 inch diameter f/2.0 parabola can be replicated to $1/4 \lambda$ accuracy with respect to the paraboloidal master.

Four inch diameter parabolas having an f/no less than f/2.0 or f/2.0 parabolas having a diameter greater than 4 inches cannot be replicated to $1/4 \lambda$ accuracy with respect to the paraboloidal master curve, using
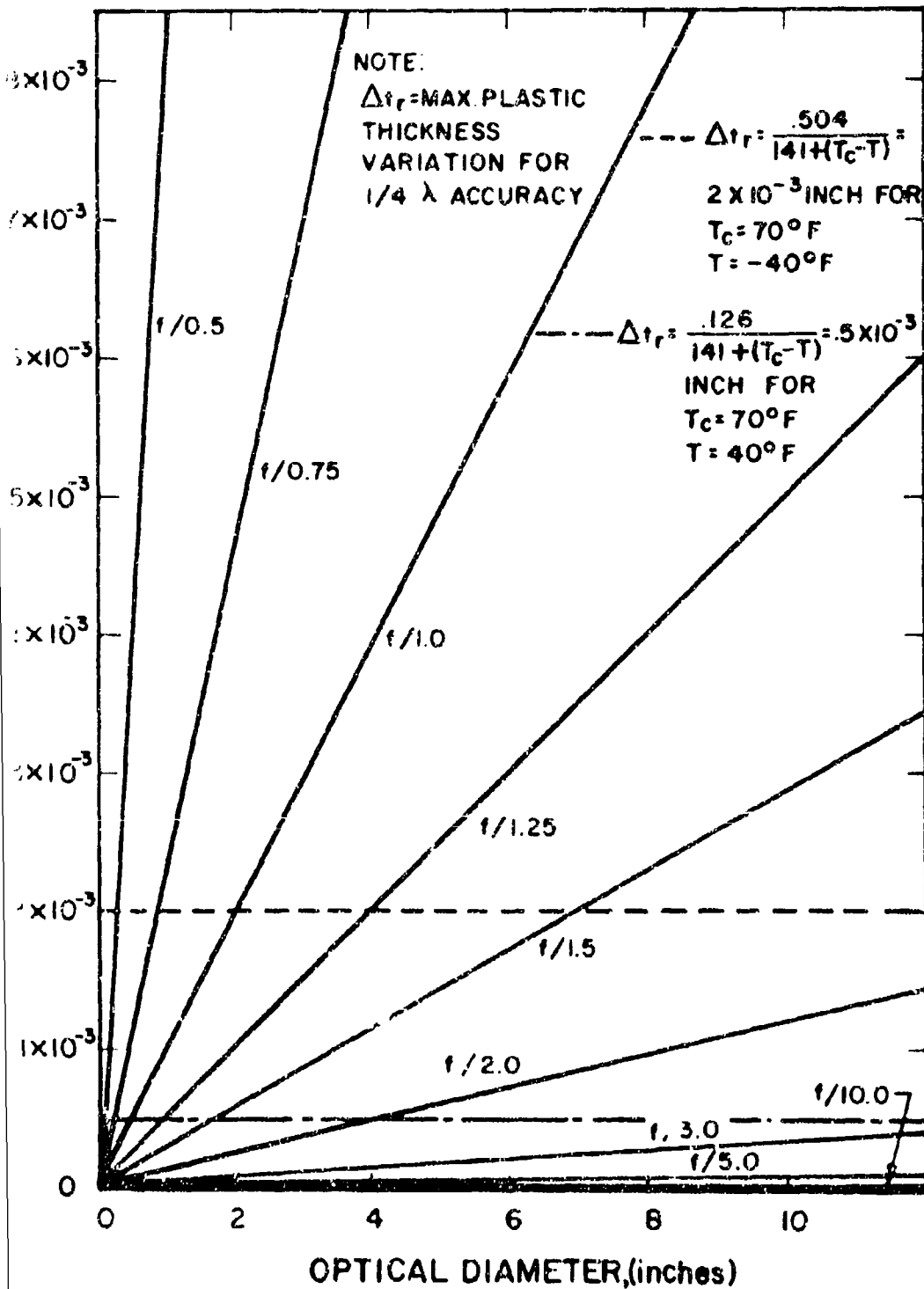
FIC. A-2 RIM-SPHERE-PARABOLOID DIFFERENCES VS DIAMETER FOR VARIOUS f/NOS

a spherical preform. However, greater plastic thickness variations are allowable if the paraboloidal focal length is allowed to vary slightly. Let the best fit parabola be given by

$$y' = \frac{x^2}{4f'} \tag{11}$$

The coordinates for the replica after replication are given by

$$y = \frac{x^2}{4f} + \delta_y \Delta \tag{12}$$

where

$$\delta_y = -6 \times 10^{-3} - 4.24 \times 10^{-5} (T_c - T) \tag{13}$$

$$\Delta = \frac{x^4}{64f^3} \tag{14}$$

Therefore, the difference between the best fit parabola and the actual coordinates, dy', is given by

$$dy' = -\frac{x^2}{4f'} - \frac{x^2}{4f} - \delta_y \Delta \tag{15}$$

This formula reduces to

$$dy' = \frac{x^2 \, df}{4f^2} - \delta_y \Delta \tag{16}$$

Assuming that the best fit parabaloid intersects the original parabaloid at the rim and vertex the difference in focal length can be determined by the following equation at the rim where $x = x_o$

$$\frac{df}{x_o} = \frac{4f^2 \sigma \Delta_o}{x_o^2} = \frac{-\delta_y x_o^2}{16f} \quad \text{where } x_o = \text{rim radius} \tag{17}$$

Combining Eqs. 16 and 17 yields

$$dy' = + \frac{\delta_y}{64f^3} (x^2 x_o^2 - x^4) \tag{18}$$

Differentiating with respect to x and setting the resultant = 0 to find the x at which maximum dy' occurs yields the relationship

$$x_{dy'max} = \frac{x_o}{\sqrt{2}} \tag{19}$$

Substituting Eq. 19 into Eq. 18 yields a total deviation of 1/4 that calculated for the deviation from the paraboloidal master curve. This means that the plastic thickness variation can be increased four times or

$$\Delta t_r' = \frac{0.504}{141 + (T_c - T)} \text{ inches where } T_c \text{ and } T \text{ are in } {}^{o}F \tag{20}$$

as plotted in Figure A-2 this variation criteria indicates that a 4-inch diameter parabaloid having an f/number of f/1.25 can be fabricated from a spherical preform and still maintain quarter wavelength accuracy from a best fit resultant parabaloid.

Another shrinkage phenomenon also affects the replication accuracy. This phenomena is the curling of the preform due to plastic cure shrinkage. This will be discussed extensively in Section A.2.2, but for the purpose of this discussion, a total deviation of 1/4 wavelength (sagitta) will be assumed from the desired parabaloid. For a flat or large f/number mirror i.e., when the mirror slope $\approx$ 0 preform rigidity is a function of x^2 the total deflection due to curling is given by the formula

$$Y = \frac{x^2}{x_o^2} \frac{\lambda}{4} \tag{21}$$

A new best fit parabola will have the form

$$y'' = \frac{x^2}{4f''} \tag{22}$$

and the resultant replica parabola curve will have the form

$$y = \frac{x^2}{4f} + \delta_y \Delta + \frac{x^2}{x_o^2} \frac{\lambda}{4} \tag{23}$$

the net difference between these curves is then given by

$$dy'' = \frac{x^2}{4f''} - \frac{x^2}{4f} - \delta_y \Delta - \frac{x^2}{x_o^2} \frac{\lambda}{4} \tag{24}$$

which reduces to

$$dy'' = \frac{x^2}{4f^2} \frac{df'}{} - \delta_y \Delta - \frac{x^2}{x_o^2} \frac{\lambda}{4} \tag{25}$$

since y'' and y are equal at $x = 0$ and $x = x_o$, then the f' is by

$$df' = -\frac{\delta_y x_o^2}{16f} - \frac{f^2 \lambda}{x_o^2} \tag{26}$$

By combining Eqs. 25 and 26 the difference between curves is given by

$$dy'' = +\frac{\delta_y}{64\ f^3} [x_o^2\ x^2 - x^4]$$

which is the same as Eq. 18 such that the net result is that curling of the replicas due to adhesive shrinkage will have little or no effect on the total allowable plastic thickness variations. The assumptions used here will be discussed more fully in Section A.2.2.

It therefore, can be concluded that, using the plastic material properties described above, parabolas with an f/no of less than f/1.25 for a 4 inch diameter will require near parabaloidal preforms and also that parabolas of f/1.25 for diameters greater than 4 inches will also require near parabaloidal preforms. From Eqs. 7 and 20, it is also apparent that a reduction in the term (T_c-T) will result in an increased plastic surface variation tolerance. For

operating temperature ranges near the curing temperature, this would result in a plastic thickness variation tolerance of better than twice those figures calculated above.

A.2.2 Analysis of Parallel Shrinkage Effects on Replica Accuracy

Consider a unit volume of thickness $(t_r + t_p)$, width, dz, and length, dx, shown below:
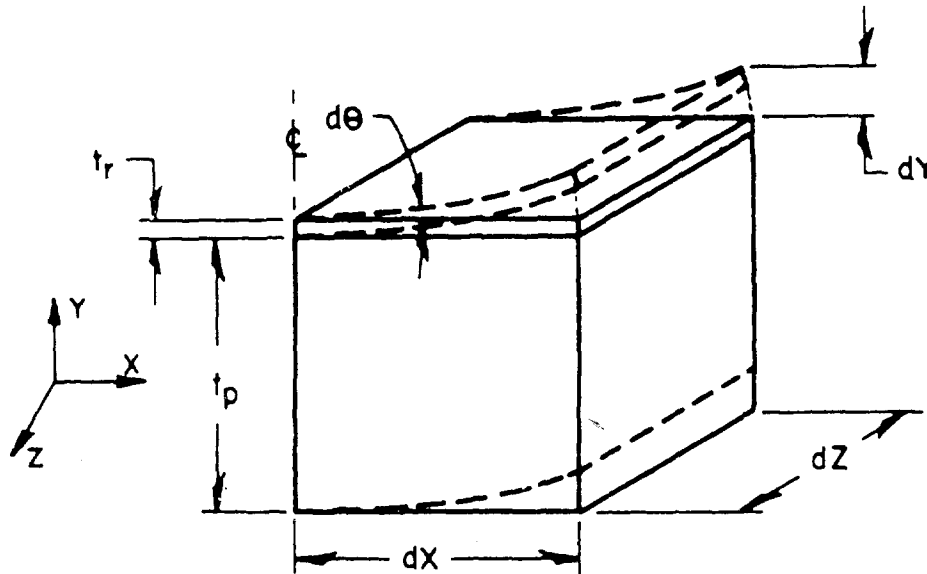
The stresses acting in the x-axis produce a force of

$$(F_x)_x = s_{rx} \, dA_{(t_r, \, dz)} \tag{27}$$

Assuming that the force acts on a backing structure with a Poisson's ratio of υ_p, the stresses acting in the z-axis produce a force in the x-axis of

$$(F_x)_z = -\upsilon_p s_{rz} dA_{(t_r, \, dz)} \tag{28}$$

Since the adhesive and backing structure are isotropic

$$s_{rx} = s_{rz} \tag{29}$$

Therefore, substituting Eq. 29 in Eq. 28 and adding Eq. 27 and Eq. 28

$$\sum F_x = s_{rx} (1 - \upsilon_p) \, dA \tag{30}$$

$$dA = t_r dz \tag{31}$$

Substitute Eq. 30 in Eq. 29

$$\sum F_x = s_{rx} t_r dz \, (1 - v_p) \tag{32}$$

This force acting at the resin midpoint, $t_r/2$ times, the radius to the neutral axis of the composite structure equals a moment M. Assume that $t_r \ll t_p$ and $E_r \ll E_p$, which is a good assumption since $t_p > 200 \times t_r$ and $E_p > 30 \times E_r$. Therefore

$$M = \sum F_x \frac{t_p}{2} \tag{33}$$

Substitute (6) in (7)

$$M = s_{rx} \, \dot{t}_r \, dz \, (1 - v_p) \frac{t_p}{2} \tag{34}$$

The adhesive skin stress, s_{rx}, results from:

1. Shrinkage during curing of the adhesive
2. Differential thermal expansion between adhesive and preform, where temperatures are measured from the temperature of cure, T_c.

Stress may be written

$$s_{rx} = s_{rz} = s_{cr} + s_{trc} + s_{tr} \tag{35}$$

The resin shrinkage δ_r is given by:

$$-\delta_r = \frac{s_{rx} - v_r s_{rz}}{E_r} \tag{36}$$

Substitute (3) in (10)

$$s_{rx} = \frac{-\dot{\delta}_r E_r}{(1 - v_r)} \tag{37}$$

Since the preform is more rigid than the adhesive, assume that all the strain occurs in the adhesive. The skin stress due to adhesive cure shrinkage is

$$s_{crx} = \frac{-\delta_{cr} E_r}{(1 - v_r)} \tag{38}$$

The skin stress due to thermal expansion is:

$$s_{trx} + s_{trcx} = \frac{(k_{tp} - k_{tr})(T - T_o) E_r}{(1 - v_r)} + \frac{(k_{tp} - k_{tr})(T_c - T_c) E_r}{(1 - v_r)} \tag{39}$$

(A positive sign indicates a tensile stress.) Combining Eq. 38 and 39 gives

$$s_{rx} = \frac{\left[-\delta_{cr} + (k_{tp} - k_{tr})(T - T_c) \right] E_r}{(1 - \upsilon_r)} \qquad (40)$$

From Ref. 7, the slope at the free end of the volume element above (neglecting t_t and E_r) is

$$\theta_x = \frac{M \cdot x}{E_p I} \qquad (41)$$

Where I is the section modulus. Therefore,

$$d\theta = \frac{Mdx}{E_p I} \qquad (42)$$

The section modulus for the unit volume (neglecting t_r) is

$$I = \frac{dz \, t_p^3}{12} \qquad (43)$$

Substituting Eq. 34 and Eq. 43 into Eq. 42 gives

$$d\theta_x = \frac{s_{rx} t_r dz \frac{t_p}{2} (1 - \upsilon_p) \quad dx}{\frac{E_p \quad dz \, t_p^3}{12}} \qquad (44)$$

Integrating Eq. 44 gives

$$\theta = \frac{6 \, s_{rx} t_r \, x}{E_p t_p^2} (1 - \upsilon_p) \qquad (45)$$

The deflection dY is given by

$$dY = \tan \theta \, dx \qquad (46)$$

But $\tan \theta = \theta$ for small angles. Then

$$dY = \theta dx \qquad (47)$$

Substitute Eq. 45 in Eq. 47 and integrate

$$Y = \int_0^{D/2} \frac{6 s_{rx} t_r}{E_p t_p^2} (1 - \upsilon_p)\, x\,dx \tag{48}$$

$$= \left. \frac{3 s_{rx} t_r x^2}{E_p t_p^2} (1 - \upsilon_p) \right|_0^{L/2} \tag{49}$$

$$= \frac{3}{4} \frac{t_r D^2 s_{rx}}{t_p^2 E_p} (1 - \upsilon_p) \tag{50}$$

Substitute Eq. 40 in Eq. 50

$$Y = \frac{3}{4} \frac{t_r D^2}{t_p^2} \frac{E_r}{E_p} \left[-\delta_{cr} + (k_{tp} - k_{tr})(T - T_c) \right] \frac{(1 - \upsilon_p)}{(1 - \upsilon_r)} \tag{51}$$

For the calculations the following typical condition were assumed:

$T_c = T_o = 70^{\circ}F$

$k_{tr} = 2.83 \times 10^{-5}$ in/in $^{\circ}F$ for Epon 828

$E_r = $ (Given in Figure A-3)

$\delta_{cr} = -4 \times 10^{-3}$ in/in for Epon 828

$t_r = 2 \times 10^{-3}$ in.

$D = 2.5$ in.

$t_p = 0.5$ in.

$\upsilon_r = .25$

$\left. \begin{array}{l} \upsilon_p = \\ k_{tp} = \\ E_p = \end{array} \right\}$ (See Table A-1)

EPON 828 RESIN
CURING AGENT Z, 20 PHR
NO FILLER
CURED 2 HOURS AT 175°F
            2 HOURS AT 300°F
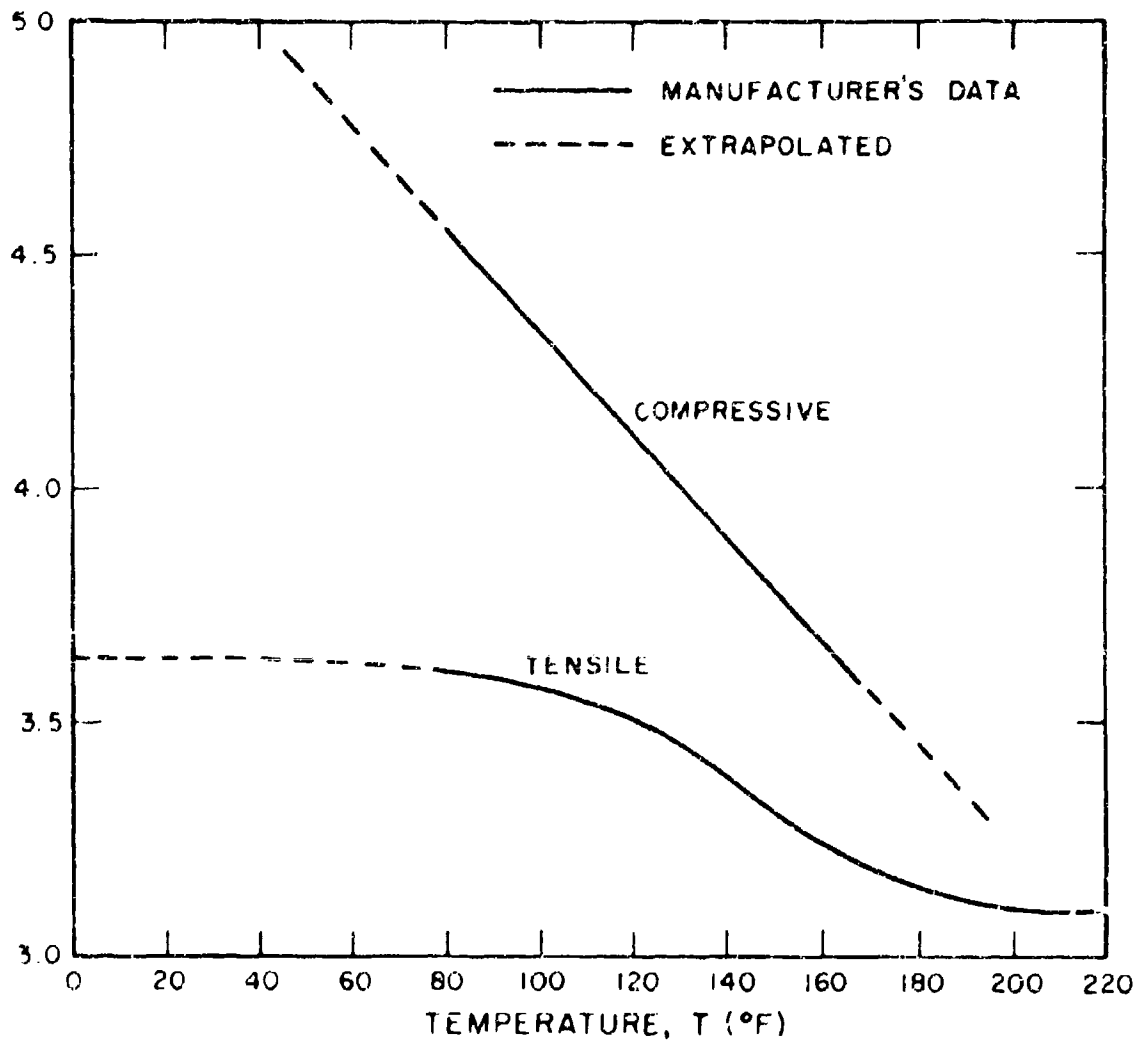
FIG. A-3   ELASTIC MODULES VS TEMPERATURE FOR AN EPOXY RESIN

TABLE A-I

PROPERTIES OF POSSIBLE BACKING STRUCTURE MATERIALS

Material	E_p (lb/in.^{2})	k_{tp} (in./in.°F)	υ_p
Borosilicate Glass	10×10^6	1.8×10^{-6}	.10
Pyrex Glass	10×10^6	$.8 \times 10^{-6}$	.10
Aluminum	10×10^6	12.8×10^{-6}	.36
Beryllium	44×10^6	6.4×10^{-6}	.10
Beryllium-copper	19×10^6	14.5×10^{-6}	.25
Steel	30×10^6	5.6×10^{-6}	.30
Invar	21.5×10^6	$.8 \times 10^{-6}$	.25
Molybdenum	51.4×10^6	2.9×10^{-6}	.25
Tungsten	51.7×10^6	2.5×10^{-6}	.25

The deflection, Y, of the preform is shown in Figure A-4 as a function of temperature for the various materials. If the cure temperature, T_c, is some value other than $T_o = 70^\circ F$, the deflection at any temperature T can be approximately found by substituting T' for T on Figure A-4.

where $T' = T - (T_c - T_o)$

Then when

$T_c > T_o$, Y vs T curves are displaced to the right by $(T_c - T_o)$ $^\circ F$

and when

$T_c < T_o$, Y vs T curves are displaced to the left by $(T_o - T_c)$ $^\circ F$.

This technique is approximate because Young's modulus for the adhesive, E_r is not a constant, but is a function of T.

Analysis of simple preforms indicates that deflection for a given diameter can be minimized by either:

Increasing: t_p, E_p, ν_p

or

Decreasing: t_r, δ_{cr}, T_c, E_r, ν_p, $(k_{tr} - k_{tp})$

Therefore, from an analysis standpoint, the problem is basically one of proper preform material selection, adhesive selection, and preform tolerances (to reduce t_r).

It appears from the above analysis that the effect of adhesive layer thickness variation is more important than preform bending induced by adhesive skin stress.

Next consider the deflection of a spherical replica assuming the stress in Eq. 39, calculated for a flat replica

$$M = \left| \frac{\sigma_{rx} t_p t_{rv}}{2} \right| (1 - \nu) = \frac{E \ I \ dR_{cx}}{2R_o^2} \quad (\text{Ref. 1}) \tag{52}$$

$$I = \frac{t_p^3 w}{12} \tag{53}$$
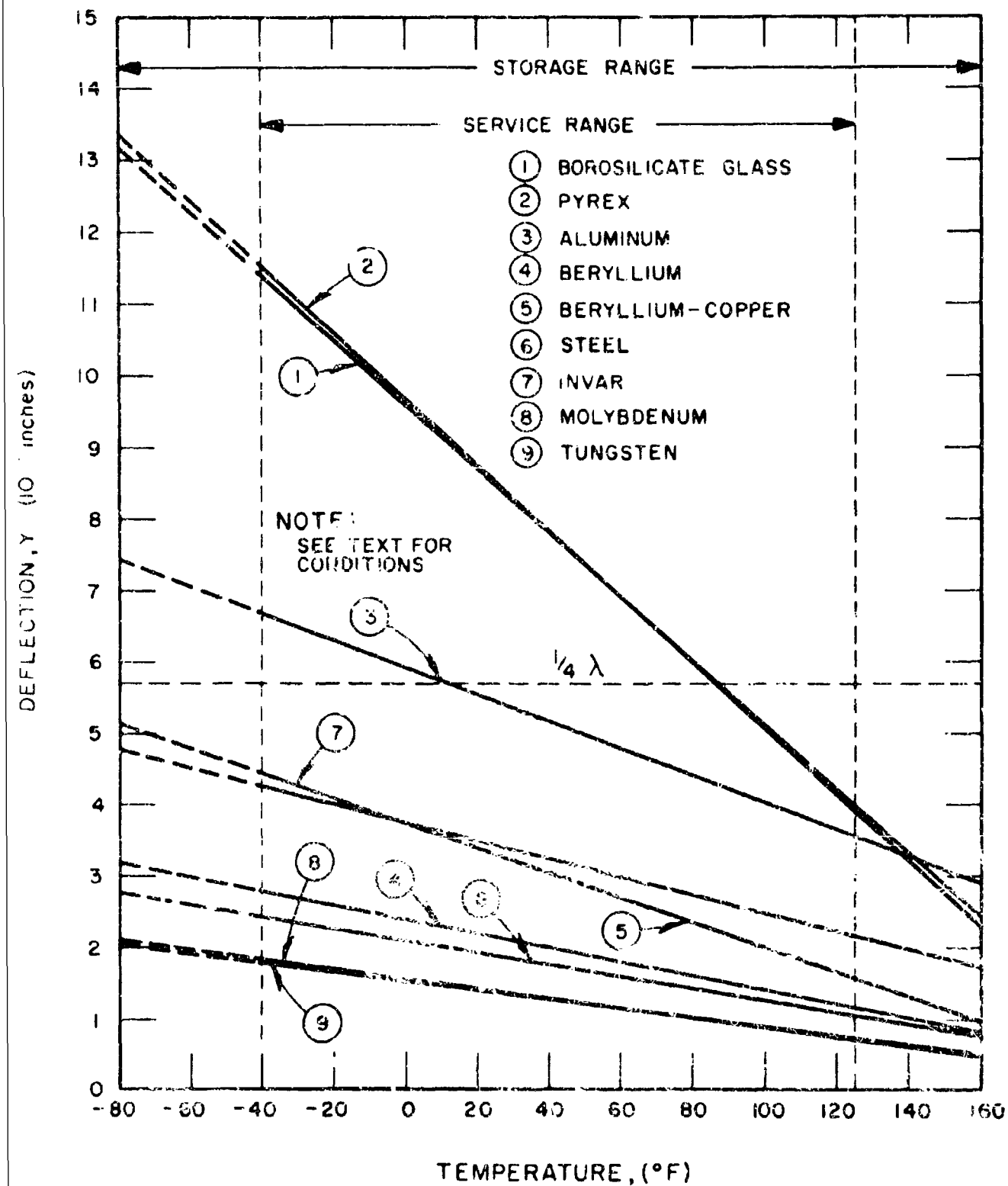
FIG. A-4   PREFORM BENDING DUE TO RESIN SKIN STRESS - TYPICAL CASE

$$dR = \frac{12 R_o^2 t_r s_{rx} (1 - \nu_p)}{E_p t_p^2} \tag{54}$$

Assuming the conditions above with a T of $-40°F$ and an aluminum preform

$$s_{rx} = 2.86 \times 10^{+3} \text{ lb/in.}^2$$

$$dR = 2.06 \times 10^{-5} R_o^2$$

as a first approximation the Sagitta $\approx \dfrac{r^2}{2R_o}$ (55)

$$\Delta \text{Sagitta} \approx \frac{r^2 dR}{2R_o^2} \tag{56}$$

$$\approx 1.03 \times 10^{-5} r^2 \text{ variation from the surface between the spherical master}$$

This means that any spherical replica will remain spherical after replication. The maximum radius change will then be $2 \times 10^{-5} R_o^2$ and the maximum Sagitta difference $1 \times 10^{-5} r^2$.

Next consider the effect of plastic stress on paraboloidal replica surface accuracy assuming that the plastic stress can be represented by the stress for a flat as in Eq. 40 above.

For a parabola

$$dR = \int_{R_o}^{R_1} d (dR_{cr}) \tag{57}$$

$$dR = \frac{24 s_{rx} t_r (1 - \nu_p)}{E_p t_p^2} \int_{R_o}^{R_1} R dR \tag{58}$$

$$= \frac{12 s_{rx} t_r (1 - \nu_p)}{E_p t_p^2} (R_1^2 - R_o^2) \tag{59}$$

Assume a paraboloid $y = \dfrac{x^2}{4f} + \dfrac{z^2}{4f}$ (60)

where f = focal length

and that the effective radius of any point on the paraboloid measured from the point 0, 2f,

$$R_1^2 = x^2 + z^2 + (2f - \frac{x^2 + z^2}{4f})^2 \qquad (61)$$

Consider the problem in 1 plane only so that $z = 0$. Then

$$R_o = 2f \text{ for a parabola} \qquad (62)$$

$$\therefore R_1^2 - R_o^2 = \frac{x^4}{16f^2} \qquad (63)$$

From Eq. 59 and Eq 63

$$dR = \frac{3 s_{rx} t_r (1 - \nu_p) x^2}{4 E_p t_p^2 f^2} \qquad (64)$$

$$= \frac{K}{t_p^2} \frac{x^4}{f2} \qquad (65)$$

Compare the parabola after shrinkage with a new parabola

$$y_1 = \frac{x^2}{4f_1} \qquad (66)$$

Where x is the same for both parabolas.

The vertical curve error d (y) is given by the term

$$dy = \frac{x^2}{4f_1} - \frac{x^2}{4f} - dR_y \qquad (67)$$

From the above typical conditions

$$\frac{K}{t_p^2} = 1.29 \times 10^{-6}/\text{in. and } K = 5.16 \times 10^{-6} \text{ in.}$$

$$dR_y = dR \cos \tan^{-1} \frac{dy}{dx} \qquad (68)$$

$$\frac{dy}{dx} = \frac{x}{2f_1} \qquad (69)$$

$$\cos \tan^{-1} \frac{dy}{dx} = \frac{1}{(1 + \frac{x^2}{4f_1^2})^{1/2}} \qquad (70)$$

$$\therefore \ dy = - \frac{K x^4}{(1 + \frac{x^2}{4f^2})^{1/2}} + \frac{x^2}{4} \frac{f - f_1}{f_1 f} \qquad (71)$$

Both parabolas match at $x = 0$ and $x = x_0$ so that $dy = 0$ at $x = 0$ and x_0
and

$$\frac{df}{f^2} \approx \frac{f - f_1}{f_1 f} \qquad (72)$$

substituting Eq. 72 in Eq. 71

$$df = \frac{4K x_0^2}{(1 + \frac{x^2}{4f^2})^{1/2}} \qquad (73)$$

$$= \frac{4K x_0^2}{(1 + \frac{x^2}{4f_1^2})^{1/2}} \qquad (74)$$

$$dy = - \frac{K x^4}{f^2 (1 + \frac{x^2}{4f_1^2})^{1/2}} + \frac{K x_0^2 x^2}{f^2 (1 + \frac{x^2}{4f_1^2})^{1/2}} \qquad (75)$$

$$d(dy) = 0 = -\frac{4Kx^3}{f^2 \left(1 + \frac{x^2}{4f_1^2}\right)^{1/2}} + \frac{2 \times K \times o^2}{f^2 \left(1 + \frac{x^2}{4f_1^2}\right)^{1/2}} \qquad (76)$$

$$x = \frac{x_o}{\sqrt{2}} \qquad (77)$$

which is the same as Eq.

$$\therefore dy = \frac{K x_o^4}{4f^2 \left(1 + \frac{x^2}{4f_1^2}\right)^{1/2}}$$

$$= \frac{K x_o^4}{4f^2 t_p^2 \left(1 + \frac{x^2}{4f_1^2}\right)}$$

assume that $\dfrac{x_o}{t_p} \approx$ constant $= 4$
then

$$dy = \frac{4K x_o^2}{f^2 \left(1 + \frac{x^2}{4f_1^2}\right)}$$

$$= \frac{K}{(f/no)^2 \left(1 + \frac{1}{32(f/no)^2}\right)^{1/2}}$$

$$\approx \frac{K}{(f/no)^2}$$

$$= \frac{5.16 \times 10^{-6}}{(f/no)^2} \text{ inches}$$

This indicates that $1/4 \lambda$ accuracy can be attained (disregarding roughness and plastic thickness defects) as long as the f/number is greater than 1 or as long as

$$tp = \frac{x_o}{4(f/no)}$$

APPENDIX B

THIN FILM PLASTIC REPLICATION PROCESS DESCRIPTION

The purpose of this appendix is to outline the process details for the fabrication of thin film plastic replicas. The scope includes the basic equipment and materials required, operational procedures, some precautionary measures and other related details. For continuity, the Process Flow Diagram, Fig. B-1, is used as the process outline. The format of this appendix is to use the Flow Diagram step numbers as section and subsection numbers for reference between the text and flow diagram.

B.1 MASTER

The surface quality and accuracy of the finished replica is limited by the initial master quality and accuracy plus the wearing characteristics of the master in production. Therefore the master specifications defined for procurement must be explicit and well engineered.

B.1.1 Procurement

The angular accuracy and the surface quality of the master should be better than the specifications of the desired replica. A factor of two is the recommendation at this time. Many replica elements may require an even greater margin for error, particularly if the desired replica approaches astronomical tolerances.

Where accuracy and surface quality requirements are high, master materials should be chosen from the following list tabulated in descending order of preference:

1. Quartz or fused silica
2. BSC-2

REPLICATION PROCESS FLOW DIAGRAM
(CONCAVE MASTER)

TASK	\. 1. Master	2. Preform, Submaster	3. Replication, Submaster	4. Subma...e	5. Preform	6. Rep...ation, Final	7. Replica
.1 Procurement / Parting	1.1	2.1		4.1	5.1		7.1
.2 Receiving / In Process Inspection	1.2	2.2		4.2	5.2		7.2
.3 Cleaning	1.3	2.3		4.3	5.3		7.3
.4 Coating	1.4			4.4			7.4
.5 Plastic Preparation			3.5			6.5	
.6 Plastic Application			3.6			6.6	
.7 Joining or Layup			3.7			6.7	
.8 Curing			3.8			6.8	7.8
.9 Final Inspection							7.9
.10 Packaging-Shipment/Storage							7.10

Note: With a convex master the sequence would go 1.4 → 3.7; 2.3 → 3.6; 1.4 → 6.6; 5.3 → 6.7

FIG. B-1 REPLICATION PROCESS FLOW DIAGRAM

APPENDIX B

THIN FILM PLASTIC REPLICATION PROCESS DESCRIPTION

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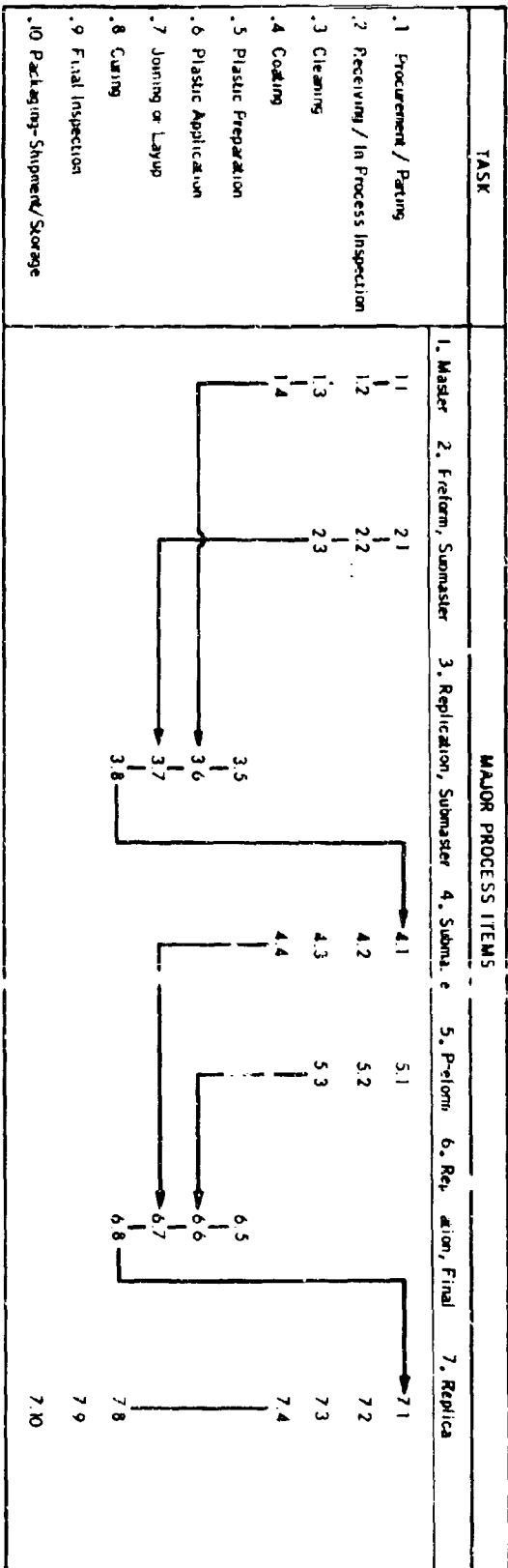
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Where accuracy and surface quality requirements are high, master materials should be chosen from the following list tabulated in descending order of preference:

1. Quartz or fused silica
2. BSC-2

3. Pyrex

4. Stainless steel 440, 304

5. Kanigen coated steel

6. Tungsten carbide

Where accuracy and surface quality are nominal, masters can be made from the following list which is tabulated in descending preference order:

1. Tungsten carbide

2. Stainless steel 440, 304

3. Quartz or fused silica

4. Kanigen coated steel

5. BSC-2

6. Pyrex

(This listing of materials is based on developments and tests of a limited number of optical shapes. This listing should not be construed as a reflection on any material quality or manufacturer. The general sequence seems logical based on available experience and analysis. Recommendations throughout this description are made with similar reservations.)

Masters should be at least 1/4 inch larger than the replica if no submaster is employed, 1/2 inch larger if a submaster is used. Ideally the oversize should be 1/2 and 1 inch larger respectively. This overage permits allowance for chamfering, area for edge roll or other out of tolerance condition, room for parting and alignment fixtures to hold the master edge, and a rim for plastic flash so that the flash will not tend to bond to the ground sides of the master.

The edges of the master should be liberally chamfered to reduce cracks from forming due to process handling and parting. The master back should be at least flash polished to permit observation during processing or to inspect the submaster or replica made from the master after replication.

The master thickness should approach those criteria used for astronomical telescope mirrors; i.e., a thickness to diameter ratio of

about 6. Another rigidity relationship can also be used. For constant master rigidity, the ratic $\frac{d2}{t3}$ should be kept nearly constant for various sizes when using the same master materials, where d is the exact or equivalent diameter of the master and t is the minimum thickness. For glass, this ratio should be below 25; the exact ratio would depend on the optic configuration.

Where metal masters are used, parting fixture attachment can be built into the master before grinding and polishing.

Masters should be procured with durable shipping and storage containers to increased storage life.

B.1.2 Master Inspection

B.1.2.1 Equipment

The specific inspection equipment required for master inspection depends on the optic inspected. However, the following are considered useful in most cases:

1. Monochromatic light source - laser, sodium or mercury light
2. Optical flat(s) - flat both sides
3. Collimator
4. Optical bench with pinhole light source, projection microscope, and optical mounts
5. Foucalt knife-edge tester
6. Ronchi tester
7. X-Y micrometer stage
8. Interferometer
9. Temperature controlled test room
10. Sphereometer
11. Optical test plates
12. 10X eyeloop
13. 100 watt incandescent light source
14. Micrometers, scales and gage blocks

B.1.2.2 Optical Tests

The optical tests used to check the surface accuracy will vary. Whatever the surface geometry, the surface quality should be rigidly inspected for out of tolerance digs, pits, and scratches.

Surface defects replicate very well. Also any defects act as nucleii for master attrition and, therefore, tend to shorten master life particularly with masters made from glass type materials.

Since surface defects are particularly important to the results and economics of the replication process, optical or mechanical tests that require physical or near-physical contact should be avoided where possible.

B.1.3 Master Cleaning

The cosmetic quality of the finished replica, as well as the master life, depend strongly on the master cleaning process.

B.1.3.1 Equipment

The master cleaning equipment desirable but not necessarily required includes:

1. Winfield type dust-free air bench
2. Centrifuge or spin table with dust-free hot air source

B.1.3.2 Materials

1. Anionic detergent
2. Trichlorethylene
3. Precipitated calcium carbonate
4. Hydrochloric acid
5. Nitric acid
6. Isopropyl alcohol
7. Acetone
8. Cotton swabs
9. Clean, lint-free linen cloth

B.1.3.3 Cleaning Procedure

For new glass masters the following cleaning procedure is recommended:

1. Liquid detergent wash (Joy)
2. Warm water rinse
3. Distilled water rinse
4. Drying
5. Trichloroethylene (applied with cotton)
6. Concentrated nitric acid (applied with cotton swab)
7. Water rinse
8. Hard rubbing with precipitated calcium carbonate (or chalk)
9. Warm water rinse
10. Concentrated hydrochloric acid (applied with cotton)
11. Water rinse
12. Distilled water rinse
13. Drying
14. Isopropyl alcohol (applied with cotton)
15. Acetone (applied with cotton)
16. Fogging with the breath and wiping with clean cotton cloth, alternately spin dry on a centrifuge with warm air and water

Steps 6 and 7 can be eliminated if there is no initial gross clean contamination of the master. Step io should be on the dust free air bench. Solution temperature extremes should be avoided to reduce thermal shock on the masters.

For new metal masters the procedures are identical to glass master cleaning with the following exceptions:

1. No acid is used in the cleaning process
2. The precipitated chalk treatment must not be as vigorously applied as with a glass master.

Metal surfaces will develop sleeks under repeated vigorous precipitated chalk cleanings.

Upon completing a replica mirror, the master surface will be contaminated with residual release coating and epoxy flash. This surface contamination must be removed before the master is used again. The first cleaning step involves rubbing the master surface with acetone-soaked cotton swabbing. This procedure loosens the epoxy flash and removes the bulk of metal release coating. The remainder of the cleaning procedures remain the same as those described for glass or metal masters.

B.1.4 Master Coating

Two alternate coating systems can be used in coating the master. One system involves the deposition of a release coating, only. In the other system, both the release and final replica coatings are deposited at the same time. To date, the latter method, although it has good economic possibilities, has not been developed sufficiently. This section discusses the deposition of the release coating only.

B.1.4.1 Equipment

1. Vacuum coating chamber with electrode, power supply, monitor, vacuum gages, viewing port

2. Holding fixtures

B.1.4.2 Materials

Copper is the recommended material.

B.1.4.3 Coating Sequence

The master is placed in the vacuum system in a suitable edge fixture (ideally the same fixture used to mount the master during layup, curing, and parting) at a source to substrate distance of 15-inches or more. The system is evacuated to about $< 5 \times 10^{-5}$ torr. Without glow discharge, deposit a copper parting layer that is just opaque, as determined by the response of the photometer sensor or by visual observation. Admit air and remove master.

Both prolonged pumping at $< 5 \times 10^{-5}$ torr vacuum and glow discharge are to be avoided since either can improve adhesion by removing trace contaminants. This removal will decrease master life.

B.2 PREFORM, SUBMASTER

The effect of the preform on the submaster replication process is as important as that of the master and plastic resin. Therefore, the preform also must be well engineered.

B.2.1 Procurement

The submaster preform should be between 1/4 and 1/2 inch larger in size than the finished replica and 1/4 and 1/2 inch smaller in size than the initial master. Preform thickness should be determined by the preform size or diameter.

The effective preform diameter-to-thickness ratio should be at least a ratio of 6 for aluminum or glass materials, considering process stresses only. When considering the preform resistance to external forces, the ratio of $\frac{d^2}{t^3}$ should be kept constant, equal to or less than 25 for glass or aluminum. Therefore, the rigidity design criteria for both the master and submaster preform are the same when considering the structural resistance to external forces.

Preform surface finish should either be 16 rms or better or lap ground to a 3F finish on the critical preform-plastic surface. Practically any high modulus of elasticity material which can be grounded or drilled is acceptable as a preform material.

Dimensional tolerances on the critical surface should be within ±0.001 inch to achieve maximum replication accuracies.

When more than 100 to 500 preforms are procured, a casting or molding process should be considered. Special optical shapes may be economical in even smaller production units.

Preforms subject to corrosion should be given an organic or inorganic strippable protective coating for storage.

B.2.2 Inspection

  B.2.2.1 Equipment

1. Micrometer and scales

2. Dial indicator

3. X-Y micrometer stage

4. Template

  B.2.2.2 Inspection Process

Preforms should be thoroughly inspected mechanically, particularly the surface to which the plastic will be bonded. This surface can be visually checked using a template or checked more accurately using a dial bore indicator to measure the sagitta, Y height, and a micrometer stage to measure the X and Z coordinates.

B.2.3 Preform Cleaning

  B.2.3.1 Materials

1. Trichloroethylene

2. Acetone

3. Precipitated calcium carbonate

4. Cotton swabs

5. Nitric acid

6. Hydrochloric acid

  B.2.3.2 Cleaning Process

Assuming there is no preform oxidation, a typical preform cleaning process would include:

1. Trichloroethylene solvent or vapor-solvent degrease

2. Water rinse

3. Scrubbing and swabbing with a precipitated calcium carbonate paste

4. Acid rinse

   a. Nitric for aluminum

   b. Hydrochloric for steels

   c. Others use distilled water

5. Distilled water rinse

6. Rinse with triple distilled acetone

7. Air dry

If there are any "water breaks" (characteristic of grease and dirt spots) after the final distilled water rinse, repeat the cleaning procedure. To remove gross oxidation, refer to standard metal cleaning procedures.

SUBMASTER REPLICATION

(Note: There are no tasks required under Subsections B.3.1
through B.3.4).

B.3.5 Plastic Preparation

B.3.5.1 Equipment

1. Weighing scale

2. Centrifuge

B.3.5.2 Materials

1. Epoxy - EPON 828 or equal

2. Hardener - DEAPA - diethlamine-propylamine

3. Tongue depressors

4. Weighing and mixing cups

B.3.5.3 Preparation Procedures

The following procedures are used in the plastic
paration:

1. Weigh out 4 times as much EPON 828 as may be required in the
final replica (for large production runs the factor may be as
low as two times). This allows sufficient overage to reduce
void formation.

2. Weight out 9 parts per hundred weight of DEAPA hardener to an
accuracy of better than $\pm$0.2 parts per hundred of resin.

3. Mix the resin and hardener vigorously for 10 minutes using
a tongue depressor (or mixer for large quantities).

4. Degass the resin system at least 1 minute in a centrifuge;
the exa t time required depends on the acceleration,
viscosity, and amount of resin.

Hardener agent should be stored in a small container
h a tight lid. Immediately after weighing, replace the lid. This

hardener is particularly hydroscopic and has an effective full strength shelflife of much less than one year when exposed to air during normal fabrication use.

Care should be taken to avoid contacting the resin or hardener as either or both can cause skin irritation.

Resin should be used at least 30 minutes after mixing to avoid high viscosity flow problems caused by the curing plastic.

Laboratory humidity between 45 and 60 percent is recommended

B.3.5 Master Preparation

1. Place epoxy in master (if master is convex, place epoxy in concave submaster preform).

2. Pour degassed epoxy preheated to 120 to 130°F into the center of the flat or concave master.

3. Avoid the formation of bubbles in the plastic during the pouring by pouring slowly and steadily. Interrupted pouring will entrap voids.

Preheating the resin-hardener mixture decreases its viscosity and enhances spreading and wetting of the preform. Good wetting is possibly the principal contributor to a coating free of surface flaws. It allows displacement of air adsorbed onto small aspherities of the preform surface. Preheating of the master (and of the preform) with extreme care to desorb moisture and air is also recommended. This should be done at a temperature of from 215-225°F for 1 to 2 hours. Thermal shock should be avoided.

For some optical shapes, additional centrifuging of the plastic in the preform may be helpful.

B.3.7 Layup-Placement of Submaster Preform on Master

B.3.7.1 Equipment

Figure B-2 depicts the modified arbor press alignment, curing and parting fixture shown with a convex master mounted in
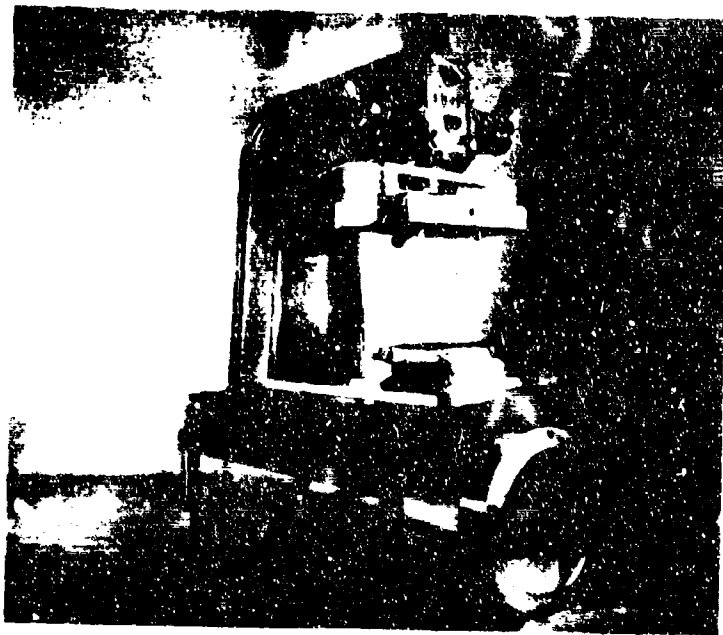
FIG. B-2 MODIFIED ARBOR PRESS, STEP NUMBER ONE

its holding fixture to the side and a concave preform held in place in the reservoir base. The press is leveled by adjusting legs with the aid of a bubble level. The rack gear arm was remachined to better than normal alignment tolerances. Other optical configurations could be similarly adapted to this modified type of fixture.

B.3.7.2 Layup

Figure B-3 shows the alignment assembly position during the plastic pouring operation. The convex master is shown in its adapter, attached to the rack gear bar. (With the replication of a concave master, the upper element is a convex preform.)

Slowly lower the top assembly onto the bottom assembly as shown in Fig. B-4. Lowering must be slow and continuous to avoid bubbles and scum on the resin surface. Alignment pins permit fine alignment adjustment in the final stages of joining the master and submaster preform.

Figure B-5 shows the convex holding fixture unscrewed and detached from the rack gear holder adapter. Figure B-6 shows the master-submaster alignment assembly detached from the modified arbor press base plate. This is now ready for curing.

B.3.8 Curing

B.3.8.1 Equipment

Forced draft, horizontal air-flow electric oven capable of maintaining a preselected constant temperature ± 0.5°C over a range of +38°C to +260°C.

B.3.8.2 Process

The master-submaster assembly is cured at 110°F for a 15 hour preliminary cure followed by a post cure of 1 hour at 175°F. The lower preliminary temperature followed by a relatively high post cure temperature gives adequate curing without inducing excessive shrinkage. The high temperature post cure has the advantage of accentuating the tendency of self-parting due to the differential thermal expansion rates when a glass master and metal preform are employed.
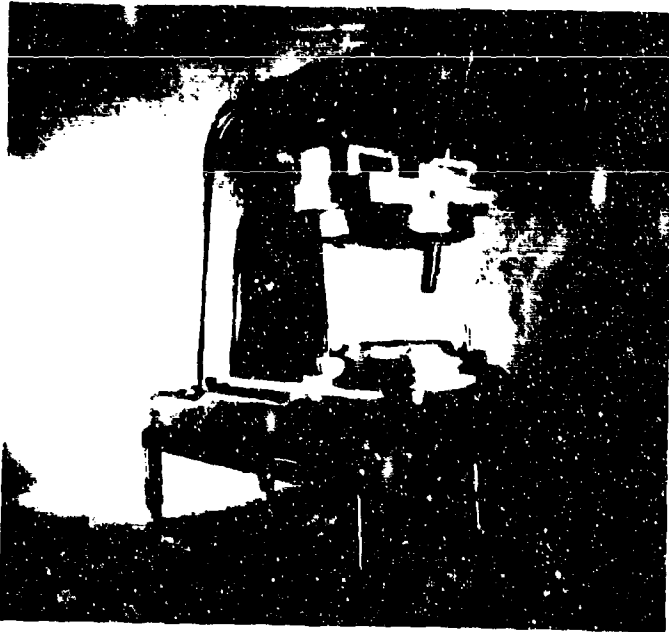
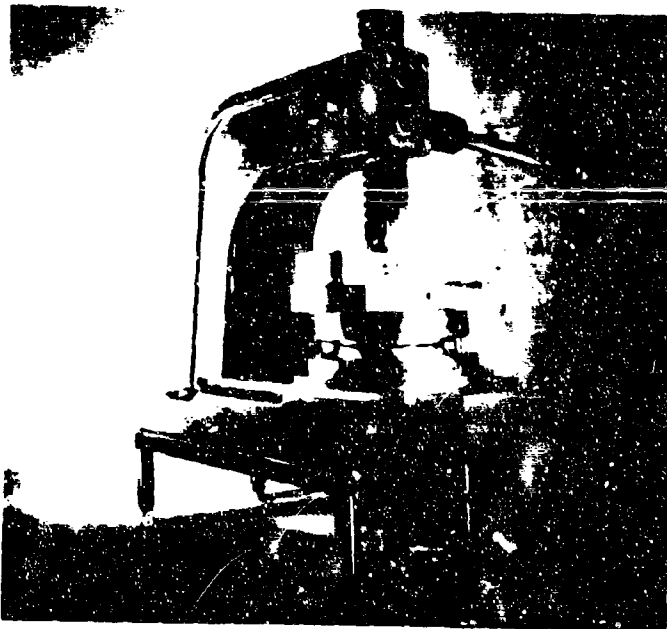FIG. B-3 MODIFIED ARBOR PRESS, STEP NUMBER TWO

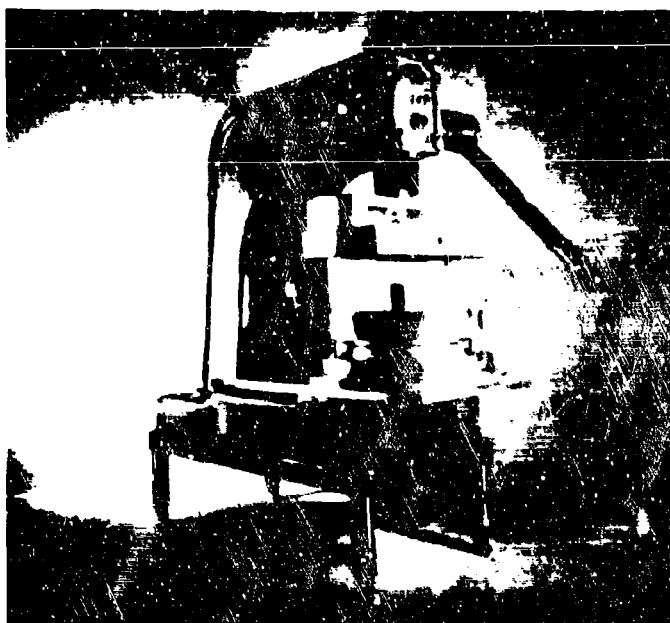FIG. B-4 MODIFIED ARBOR PRESS, STEP NUMBER THREE
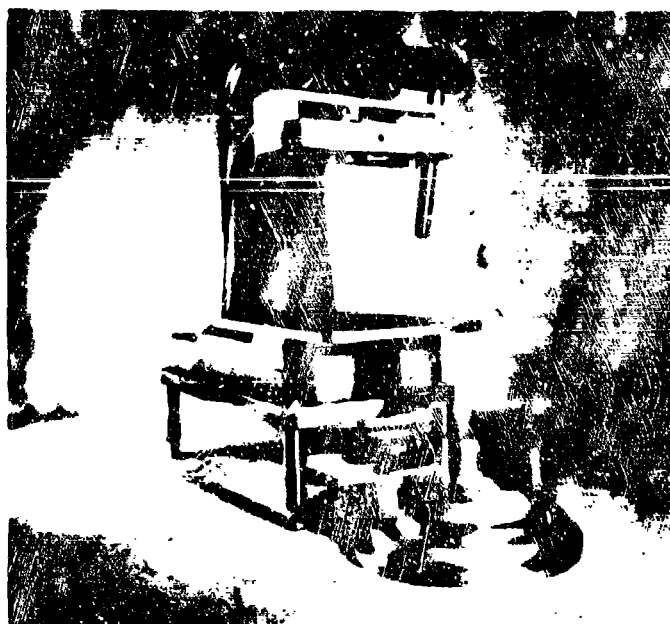
FIG. B-5 MODIFIED ARBOR PRESS, STEP NUMBER FOUR

FIG. B-6 MODIFIED ARBOR PRESS, STEP NUMBER FIVE

nimum vibration and a level oven shelf are important in producing a
igh accuracy replica with good cosmetic qualities.

B.4 SUBMASTER

B.4.1 Submaster Parting

Parting is initiated immediately after completion of the post curing cycle. While still hot, the layup is secured in the parting fixture. Slow cooling is allowed to take place. The metal preform will shrink more rapidly than the glass master due to differences in the thermal expansion coefficients. The forces generated by this differential rate of shrinkage augments the force applied by the parting fixture. Complete parting can therefore be affected with only a small external force.

If parting does not occur on the initial attempt the apparatus is allowed to cool for another 15 minutes. Gentle pressure is again exerted on the parting fixture. Parting usually occurs by this time. If parting does not occur another alternate period of cooling followed by pressure is repeated until parting is achieved. On occasion it may be necessary to slowly reheat the layup and reapply the preceding technique before parting takes place. The application of great force rarely has been needed to achieve parting.

B.4.2 Inspection

Submaster inspection is normally visual to determine whether there are gross figure defects or unacceptable surface finish. Where more accurate optical testing is required, equipment and test methods discussed in Subsection B.1.2 can be employed.

B.4.3 Cleaning

B.4.3.1 Materials

Solutions to strip aluminum, copper, and silver.

B.4.3.2 Procedure

The replica submaster surface is flooded with the appropriate stripping agent. Rinsing with tap water and distilled water follows as soon as the metal has been completely dissolved. Absolute alcohol is then poured over the replica surface and the replica is allowed to air dry.

If the submaster has been previously used in replication, resin flash may have to be removed from outside the critical optical surface by gentle swabbing with cotton and detergent or careful rubbing with a razor blade.

B.4.4 Submaster Coating

B.4.4.1 Equipment

See Subsection B.1.4.

B.4.4.2 Materials

1. Copper
2. Chromium
3. Silicon monoxide
4. Oxygen

B.4.4.3 Procedure

1. Mount the stripped replica submaster in a vacuum coater at least 15 inches from the sources.
2. Reduce the chamber pressure to less than 5×10^{-5} torr.
3. Throttle the pumps and bleed bottled oxygen into the system until a glow discharge level of 3,000 volts at 150 milliamperes is reached from a shielded aluminum cathode. The glow discharge must be carefully controlled to prevent excessive heating. Excessive heat will cause orange peel in the plastic film.
4. Using a photometer response, filtered by a Wratten No. 74 filter (peak transmission at 538 millimicrons) and a shutter between the source and submaster, deposit a 30-40 percent reflective film.

5. Follow immediately with a rapid deposition of silicon mon-
   oxide as a protective film.

6. Deposit a barely opaque copper film onto the silicon monoxide.

7. Admit air and remove submaster.

B.5 PREFORM

Details for the replica preform are the same as the submaster
preform.

B.5.1 Procurement

Same as Subsection B.2.1 except size should be 1/4 to 1/2
inch smaller.

B.5.2 Inspection

Same as Subsection B.2.2

B.5.3 Cleaning

Same as Subsection B.2.3.

B.6 REPLICATION

Details for replication are the same as for submaster replication.

B.6.1 to B.6.4 (not applicable)

B.6.5 Plastic Preparation

Same as Subsection B.3.5

B.6.6 Placement of Epoxy

Same as Subsection B.3.6 except the plastic resin is placed
either in a concave preform or submaster whereas in Subsection B.3.6
the plastic resin is placed in a concave master or submaster preform;
the shape in each section depends on the original master shape. Note
that the tooling size may have to be smaller to accommodate the smaller
preform.

B.6 . Layup - Joining Replica Submaster with Preform

Same as Subsection B.3.7

B.6.8 Cure

Same as Subsection B.3.8

REPLICA

B.7.1 Replica Parting

Same as Section B.4.

B.7.2 Inspection

Basically the same as Subsection B.1.2. Surface accuracy, ish requirements, and standards will be different, however. Reason-ie specifications will have to be defined, based primarily on system uirements rather than aesthetic considerations.

B.7.3 Cleaning

Same as Subsection B.4.1

B.7.4 Coating

(See Subsections B.1.4 and B.4.4 for equipment and materials)

1. Mount the stripped replica in a vacuum coater at least 15 inches from the sources.

2. Reduce chamber pressure to at least 5×10^{-5} torr.

3. Throttle the pumps and bleed bottled oxygen into the system until a glow discharge level of 3,000 volts at 150 milliamperes is reached from a shielded aluminum cathode. The glow dis-charge must be carefully controlled to prevent excessive heat-ing. Excessive heat will cause orange peel in the plastic film.

4. Using a photometer response filtered by a Wratten No. 74 filter, deposit a 30-40 precent reflective film.

5. Follow immediately with a rapid deposition of $\frac{\lambda}{2}$ (269 milli-microns) of silicon monoxide as determined by the reflectance falling first to a minimum at $\frac{\lambda}{4}$ and then rising to a maximum at $\frac{\lambda}{2}$.

6. Rapidly deposit aluminum to maximum reflectance as measured by the photometer.

7. Bleed oxygen into the system to maintain a pressure of 5 to 7 x 10^{-5} torr while slowly depositing a $\frac{\lambda}{7}$ thickness of silicon monoxide.

8. Wait 15 minutes.

9. Admit air and remove replica.

B.7.5, B.7.6 and B.7.7 - There are no applicable task sections for the replica item.

B.7.8 Replica Cure

Equipment required is discussed in Subsection B.3.7. Post cure the coated replica two hours at a temperature of 175°F to improve coating adhesion.

B.7.9 Final Inspection

The replica should again be checked to specifications by techniques and equipment described in Subsections B.1.2 and B.7.2 and accepted or rejected by quality control.

B.7.10 Packaging, Shipping and Storing

Package the finished replica in a dust and moisture-proof container with sufficient rigidity and packing to avoid damage during shipment or storage.

APPENDIX C

ANALYSIS OF PREFORM SHOCK RESISTANCE

1. MIRROR SHOCK STRESS

Assumptions

1. Replica mirror is mounted with the concave reflective face pointing in the direction of projectile travel

2. Edges are fixed

3. Strained configuration is constant and maximum during the 20,000-g constant acceleration period

.. Load is uniformly distributed over the entire mirror

5. A flat disc is a good model for the mirror.

These assumptions are diagrammatically shown in Fig. C-1.

The axial restraining force, F, is related to the axial strain, x, and spring constant, K, by

$$F = Kx \tag{1}$$

where

$$K = \frac{16}{3} \frac{\pi E \, \eta^2 \, t^3}{(\nu^2 - 1) \, r^2} \qquad \text{(Reference C-1)} \tag{2}$$

where E = Young's Modulus (see Table C-1) $\qquad$ (3)

$\eta = \frac{1}{\nu}$

ν = Poissons ratio (see Table C-1)

r = disc radius

t = disc thickness.

Also, F can be equated to the disc weight

$$F = m \, \ddot{X} \tag{4}$$

$$m = \text{mass} = \rho \, \pi \, r^2 \, t \tag{5}$$
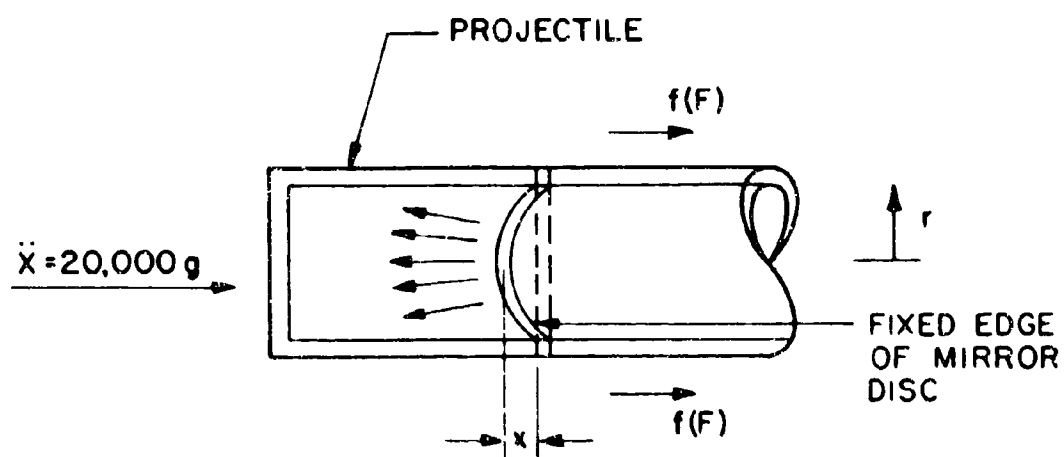
ρ = mass density

$\ddot{X}$ = acceleration.

FIG. C-1 SCHEMATIC OF MIRROR ENVIRONMENT

The maximum stress from Reference 1, $\sigma_{maximum}$, is given by

$$\sigma_{max} = \frac{3 \, F \, (\eta + 1)}{8 \, \pi \, \eta t^2} \tag{6}$$

By substitution

$$\sigma_{max} = \frac{3 \, (\eta + 1) \, \rho \, r^2 \, \ddot{X}}{8 \, \eta t} \tag{7}$$

TABLE C-1
PHYSICAL PROPERTIES

Material	E lb/in^2	ρg lb/in^3	$\sigma_{elastic\ limit}$ lb/in^2	υ (assumed)
Aluminum 2024-T3	10×10^6	0.100	50×10^3	1/3
Beryllium	44×10^6	0.070	50×10^3	1/10
Magnesium AZ31B	6.5×10^6	0.066	25×10^3	1/3
Steel 4340	30×10^6	0.280	200×10^3	1/3
416	30×10^6	0.280	100×10^3	1/3
Titanium 6 Al-4Va	15×10^6	0.170	130×10^3	1/3

And

$$X = \frac{3 \, \rho \, r^4 \, \ddot{X} \, (\eta^2 - 1)}{16 \, E \, \eta^2 \, t^2} \tag{8}$$

For the case in question

$r = 2$ inches

$t = .125$ inches

$\ddot{X} = 20,000$ g

A comparison of displacements, x, maximum stress $\sigma_{maximum}$, and ratio of maximum stress to $\sigma_{elastic\ limit}$, is shown in Table C-2.

TABLE C-2

20,000-g ACCELERATION EFFECTS ON 1/8-INCH DISC

Material	Deflection inches	σ_{max} lb/in^2	$\sigma_{max}/\sigma_{elastic\ limit}$
Aluminum 2024-T3	0.034	32×10^3	0.64
Beryllium	0.010	17×10^3	0.34
Magnesium	0.035	21×10^3	0.84
Steel 4340	0.032	90×10^3	0.45
416	0.032	90×10^3	0.90
Titanium 6Al-4Va	0.039	54×10^3	0.42

From this analysis, all the materials could withstand the shock. Since $\sigma_{maximum}$ varies with $1/t$, increasing preform thickness will decrease the stress and make the shock resistance even greater.

REFERENCE

Appendix C

Roark, R. J., "Formulas for Stress and Strain," McGraw-Hill
Book Company, 1954

E S

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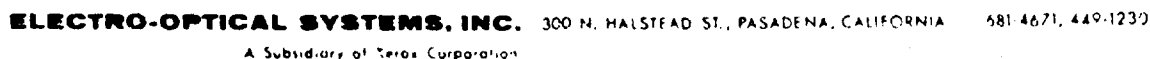
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Reference (Contract No.)   DA-04-495-AMC-376(A)

Report No. and Type 4821-Final	Date of Issue 26 February 1965
Short Title Replica Optics	Covers Period 12 February 1964– 31 August 1964
Classification U *****	EOS Classified Doc. No.

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Very truly yours,

ELECTRO-OPTICAL SYSTEMS, INC.

Richard N. Strong

Richard N. Strong, Manager
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